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NITROGEN FOOTPRINT: DEVELOPMENT AND TESTING OF NEW METHODOLOGIES FOR THE ASSESSMENT OF ENVIRONMENTAL IMPACT RELATED TO THE NITROGEN CYCLE

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Ora il compito del demiurgo autarchico, in fatto di azoto,
è quello di sopperire alla nostra agricoltura quel tanto di azoto
che il ciclo naturale non arriva a immettere naturalmente nel terreno.
(C.E. Gadda – Azoto atmosferico trasformato in pane)

Yes, there are two paths you can go by,
but in the long run
there still time to change the road you're on.
(Led Zeppelin – Stairway to heaven)

Abstract

The present research work addresses the topic of the assessment of environmental impact related to the nitrogen cycle. Starting from an analysis of the environmental effects derived from the alteration of the nitrogen cycle caused by human intervention and of the tools currently available to evaluate these effects, the objective of the research is to develop a new impact assessment methodology, based on an whole Life Cycle Assessment (LCA) approach and to verify its effectiveness in accounting and detailing the environmental impacts caused by a product system and by the related processes.

The proposed methodology overcomes some of the weaknesses identified in existing assessment tools, in particular by proposing a comprehensive LCA approach, applied at both methodological and operational level, and an orientation to the identification and accounting of environmental impacts. In particular, the methodology provides for a multistep approach that, starting from the identification of the nitrogen-containing substances of a product systems, first allows to account for reactive nitrogen and then, through specific characterization models, to assess the environmental effects for different impact categories to finally calculate, after normalization and weighting, a single stand-alone impact indicator. This approach allows identifying and accounting the environmental impacts related to the nitrogen cycle for a product system, quantifying also the contribution of the different processes and activities in the life cycle.

After the design phase, the methodology has been successfully tested in four different application cases, two based on database and two on real data collected on the field, demonstrating the validity and applicability of the proposed model and obtaining results consistent with the targets set for each application.

The proposed methodology has been defined and applied in all its phases and steps, with some computational shortcuts specially modeled on the application cases addressed in the research work: some further adaptations may therefore be required for applications in fields different from those proposed.

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Introduction

The research topic is focused on the evaluation of the nitrogen cycle and on its disruption of anthropogenic origin highlighted by several studies in recent years. The economic, environmental and social debate developed around the issues related to the nitrogen cycle is centered on a dichotomy.

From one side, it is evident that nitrogen is an essential component of many compounds found in living cells within plants, animals and humans and that the production of reactive nitrogen through natural processes from atmospheric nitrogen would be insufficient to guarantee current levels of life for humanity. The provision of reactive nitrogen forms due to anthropogenic, through mineral fertilizers, contributes greatly to the increased agricultural production needed to feed the growing world population and then to ensure food security.

From the other side, the continuous increase in production of reactive nitrogen of anthropic origin has led to a progressive alteration of the natural cycle of nitrogen, exceeding the limit defined for the planetary boundary, fixed as a safe operating space for human societies to develop and thrive. In this regard, it should be highlighted that, besides the benefits of the use of nitrogen compounds, must be taken into account that nitrogen, in its various chemical forms, plays a major role in a great number of environmental issues, causing a number of different effects connected to each other by taking part in the cycling. It contributes, in fact, to acidification and eutrophication of soil, groundwater and surface waters, to decreasing ecosystem vitality and biodiversity and causing groundwater pollution through nitrate leaching. Nitrogen compounds also play a role in carbon sequestration, global climate change, formation of ozone, oxidants and aerosols and is present in toxic compounds, potentially posing a serious threat to environment and human health.

Several research results can be found on the definition and quantification of flows of different forms of nitrogen in the environment and on caused environmental impacts. At the legislative level too, numerous acts have been issued, particularly in the legislative framework of the European Union, for the management of environmental aspects and the reduction of impacts related to nitrogen emissions in the various environmental compartments (air, water, soil), or in order to regulate some specific field (eg. industrial emissions or transport). The studies and research related to the analysis of nitrogen flows and environmental impacts are generally based on the concept of reactive nitrogen. This is commonly defined as all nitrogen forms apart from N_2 including oxidized nitrogen forms, as NO,

N_2O, NO_2, NO_3, reduced forms of nitrogen, as NH_4^+, NH_3, and organic nitrogen as proteins, amines, etc., with different states of oxidation.

In this context, some tools of “nitrogen footprint” have also been recently developed to properly study, assess, control and try to manage the release of nitrogen compounds emissions and also to support policymakers, stakeholders, producers and consumers in decision-making strategies. All the proposed tools started from the concept of reactive nitrogen that was easily extended to the next definition of “nitrogen footprint” as the total amount of reactive nitrogen released to the environment due to the resource consumption, expressed in total units of reactive nitrogen. The intended goal of these tools is to describe how reactive nitrogen is lost to the environment and its resulting impacts due to individual and collective consumption behaviors and the ways in which policy can have an effect on these losses. Addressing this specific topic, another starting point for the research work was the footprint indicator concept, comprising the main features and the applicable requirements, both as regards the formulation of the footprint indicators and their communication, with particular reference to international standards issued or under preparation by ISO and to the recent scientific publications in this field.

Subsequently, a first aim of the research, was to carry out a critical analysis of the existing nitrogen footprint tools, in order to highlight the main features of each methodology and to compare with the requirements that should ideally have a footprint indicator, according to latest research and to applicable international standards.

From these premise started the subsequent research work, which has been aimed at formulating a proposal for the assessment of environmental impacts related to the nitrogen cycle, in order to review the definition and structure of what is currently commonly defined as nitrogen footprint indicator, addressing in particular any weaknesses identified in the existing tools. Further fundamental references to take into account for the design and development of the methodology to be proposed were the LCA approach, according to the international standard of ISO 14040 series, and a structure oriented to the life cycle impact assessment.

A further objective of the research, once formulated a methodological proposal for the evaluation of the impacts related to the nitrogen cycle, has been finally to apply the proposed tool in various fields, both using a database approach and by relying on on-site collected data and analyzes, in order to verify its effectiveness in achieving the objectives set and confirm its validity.

The research findings are presented in the five chapters of the present work. In particular, in Chapter 1 are described the introductory concepts related to the nitrogen cycle, reactive nitrogen, processes for its creation, flows in the environmental compartments and related effects and a summary of European legislation on this subject. In Chapter 2, starting from the general concept of footprint, the tools currently formulated and applied for the nitrogen footprint accounting are presented and analyzed, describing the reference normative framework and identifying strengths and weaknesses. Chapter 3 is devoted to the design of the proposed methodology for nitrogen related impacts assessment, describing the assumptions for its formulation and the underlying mechanisms and mathematical models. Finally, in the Chapter 4, four different applications of the proposed methodology are presented, the first two supporting the formulation and validation of the model, the last two based on real cases, concerning the comparison of two cultivation methods and a specific application on four products of the beverage industry.

Chapter 1

Nitrogen and the environment

This chapter introduces the theme of environmental aspects related to the nitrogen cycle. In particular, the nitrogen cycle is briefly presented and the concept of reactive nitrogen is introduced, describing the processes for its creation and presenting a summary of reactive nitrogen quantification and distribution data. The mechanisms of interaction of nitrogen with the environment are then presented and the associated impacts are described.

Finally, it is summarized the reference legislative framework at European level for the control of emissions and the reduction of environmental impacts attributable to the alterations of the nitrogen cycle.

1.1 Nitrogen

Nitrogen (symbol N, atomic number 7) as a chemical element was first discovered and isolated by Daniel Rutherford in 1772. The name nitrogen derives from the Greek roots νἰτρον "nitre" and -γεννᾶν "to form" and was suggested by Jean-Antoine-Claude Chaptal because it was found that nitrogen was present in nitric acid and nitrates. Antoine Lavoisier or, according to other interpretations Louis-Bernard Guyton-Morveau, suggested instead the name azote, from the Greek άζωτικός "no life", that is used in many languages, such as Italian, French, Russian and appears in the English names of some compounds such as hydrazine, azides and azo compounds.

Nitrogen is a common element in the universe, estimated at about seventh in total abundance in the Milky Way and the Solar System. At standard temperature and pressure, two atoms of the element bind to form dinitrogen, a colorless and odorless diatomic gas with the formula N_2. Dinitrogen forms about 78% of Earth's atmosphere, making it the most abundant uncombined element. Nitrogen occurs in all organisms, primarily in amino acids (and thus proteins), in the nucleic acids and in the energy transfer molecule adenosine triphosphate. The human body contains about 3% nitrogen by mass, the fourth most abundant element in the body after oxygen, carbon, and hydrogen.

Many industrially important compounds, such as ammonia, nitric acid, organic nitrates (propellants and explosives), and cyanides, contain nitrogen. The extremely strong triple bond in elemental nitrogen (N≡N), the second strongest bond in any diatomic molecule, dominates nitrogen chemistry. This causes difficulty for both organisms and industry in converting N_2 into useful compounds, but at the same time means that burning, exploding, or decomposing nitrogen compounds to form nitrogen gas releases large amounts of energy. Synthetically produced ammonia and nitrates are key industrial fertilizers, and fertilizer nitrates are key pollutants in the eutrophication of water systems.

Apart from its use in fertilizers and energy-stores, nitrogen is a constituent of organic compounds as diverse as kevlar used in high-strength fabric and cyanoacrylate used in superglue. Nitrogen is a constituent of every major pharmacological drug class, including antibiotics. Many drugs are mimics or prodrugs of natural nitrogen-containing signal molecules: for example, the organic nitrates nitroglycerin and nitroprusside control blood pressure by metabolizing into nitric oxide. Many notable nitrogen-containing drugs, such as the natural caffeine and morphine or the synthetic amphetamines, act on receptors of animal neurotransmitters.

However more than 99% of this N_2 is not available to more than 99% of living organisms because its molecular form is not usable. Breaking the triple bond holding the two nitrogen atoms together, requires a significant amount of energy, which can be mustered only in high-temperature processes or by a small number of specialized N-fixing microbes (Galloway *et al.*, 2003).

Of the major nutrients needed for biomass production, nitrogen is most commonly the limiting one, at least in terrestrial systems: phosphorus and potassium are the other major limiting nutrients. Higher plants can mostly only use nitrogen after it has been converted to reactive forms such as nitrate (NO_3^-) or ammonium (NH_4^+). There are basically three ways of accomplishing this:

- decay of organic matter by microbes in soils (dead organisms, leaves, manure, etc.) and eventually release biologically available forms of nitrogen;
- Biological Nitrogen Fixation (BNF): nitrogen-fixing organisms (e.g. bacteria) ‘fix’ atmospheric N_2 into biologically available forms of reactive nitrogen;
- production and application of reactive nitrogen as inorganic fertilizer (Sutton *et al.*, 2011).

1.2 The Nitrogen cycle

“Fabbricare l'azoto non si può dire, poiché esso è nell'aria che respiriamo. Si dice invece fissare l'azoto, cioè captarlo dall'aria, unirlo ad altri elementi di natura, preparare dei sali azotati da spargere sui coltivi: già le radici del frumento lavorano, lavorano, nel buio della terra, ad assorbire dalla terra i composti azotati; perché anche domani il popolo vittorioso e rude possa deglutire il suo pane.

I chimici, i biologi chiamano ciclo o circolo dell'azoto il trapasso dell'azoto dall'atmosfera alla sostanza vivente delle piante, degli animali: il suo ritorno nell'atmosfera. Quali ne sono le cause? Sotto l'azione di scariche elettriche atmosferiche (scariche oscure), l'ossigeno e l'azoto dell'aria si combinano in ossido di azoto, che, raggiunto dalle acque di pioggia, dà luogo ad acido nitroso. Altro acido nitroso è procurato al terreno per l'opera dei bacteri nitrosi, dèmoni microscopici del sottoterra, scoperti da Winogradski nel 1891. Essi fabbricano acido nitroso ricavandolo dall'ammoniaca e dai composti ammoniacali; che sono tra i proventi della dissociazione organica, della putrefazione.

Una seconda categoria di bacteri, chiamati bacteri nitrici, trasforma l'acido nitroso in acido nitrico. Questo, diluito nell'acqua di circolo, al contatto delle «basi» del terreno da i sali nitrici, o nitrati, di cui le radici delle piante son ghiotte. Ecco le biade dei campi di Pansampognante, ecco il pane, la vita. Le sostanze albuminose degli steli e del seme, gli amino-acidi, il glùtine, contengono azoto e lo trasferiscono nell'organismo degli animali.

La morte degli animali e delle piante, le foglie che si spiccano e si dissolvono nell'autunno, riportano l'azoto al terreno, e la vita stessa lo restituisce man mano al circolo, per i prodotti della espirazione, del sudore, della escrezione.

Ora il compito del demiurgo autarchico, in fatto di azoto, è quello di sopperire alla nostra agricoltura quel tanto di azoto che il ciclo naturale non arriva a immettere naturalmente nel terreno. L'industria umana percorre, in rincalzo alla natura, questo arco del ciclo: dall'aria al terreno. E lo percorre lungo alcune sue strade sicure, se non facili, e solo da pochi decenni esplorate: o da pochi anni tracciate.” (Gadda, 1937).

The nitrogen cycle is commonly defined as a biogeochemical cycle that includes soil, atmosphere and biosphere, by which nitrogen is converted into various chemical forms as it circulates among the atmosphere and terrestrial and marine ecosystems.

The largest reservoir of nitrogen on the earth is the atmosphere, where nitrogen is mainly found as an inert diatomic gas (N_2) and as traces of nitrous oxide (N_2O, a greenhouse gas with great global warming potential), NO_x and volatilized ammonia. The other large reservoir on the earth is represented by rocks and sediments, while fast exchange pools such as terrestrial and aquatic biota, water and soils contain negligible nitrogen amounts (Palmeri *et al.*, 2014).

The Figure 1.1 shows a schematic representation of the nitrogen cycle whose processes are described below.

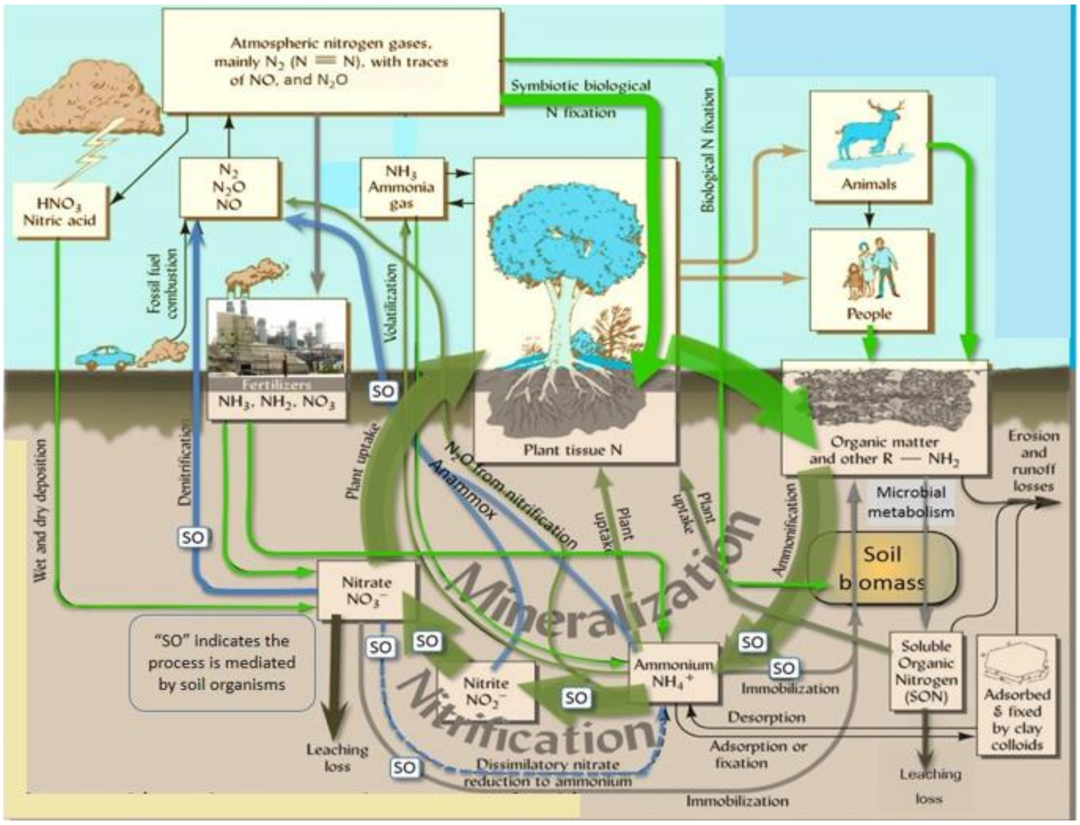


Figure 1.1. *Schematic representation of the nitrogen cycle. Blue arrows represent anaerobic processes, bright green arrows represent additions of nitrogen to soil, darker green arrows represent aerobic transformations. Source: Brady and Weil (2014).*

The main processes that constitute the nitrogen cycle can be summarized as follows:

- ***Biological Nitrogen Fixation (BNF)***. This is a natural process performed by a number of diazotrophs, such as Anabaena (a cyanobacterium), and Rhizobium (the symbiotic bacterium found in legume root nodules).
- ***Nitrogen fixation by anthropic activities***. Humans influence the nitrogen cycle mainly through industrial nitrogen fixation that consists in the conversion of N_2 into NH_3 by the Haber–Bosch process.

- ***Nitrification***. This is the oxidation of ammonia to oxyanions. The conversion of ammonium to nitrate is performed primarily by soil-living bacteria and other nitrifying bacteria. Specifically, in the primary stage of nitrification, the oxidation of ammonium (NH_4^+) is performed by bacteria such as the Nitrosomonas species, which converts ammonia to nitrites (NO_2^-): the reaction is the following:

$$NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-. \tag{1.1}$$

The oxidation of the nitrites (NO_2^-) into nitrates (NO_3^-) is performed by other bacterial species, such as Nitrobacter: the reaction is the following:

$$NO_2^- + H_2O \rightarrow NO_3- + 2H^+ + 2e^-. \tag{1.2}$$

- ***Denitrification***. Some bacteria, such as Pseudomonas, and Clostridium, in anaerobic conditions, are able to use oxidized forms of nitrogen – including, in order of most to least thermodynamically favorable, nitrate (NO_3^-), nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O) – as a terminal electron acceptor in respiration. Denitrifying microbes require a very low oxygen concentration of less than 10%, as well as organic C for energy. The complete denitrification process can be expressed as the following reaction:

$$2NO_3^- + 10\ e^- + 12\ H^+ \rightarrow N_2 + 6H_2O. \tag{1.3}$$

- ***Assimilation***. Plants assimilate nitrogen in the form of nitrate and ammonium. The nitrate assimilated is first reduced to ammonium, and then combined into organic forms, generally via glutamate. Animals generally assimilate nitrogen by first breaking protein down into amino acids.
- ***Ammonification and excretion***. When plants and animals decay, putrefying bacteria produce ammonia from the proteins they contain. Animals also produce breakdown products such as ammonia, urea, allantoin and uric acid from excess dietary nitrogen. These compounds are also targets of ammonification by bacteria.
- ***Anaerobic ammonia oxidation***. This is conversion of nitrite and ammonium to pure nitrogen gas (N_2) in seas and oceans, hot springs, hydrothermal vents, and many freshwater wetland

ecosystems, which than escapes to the atmosphere. The reaction mechanism is triggered by a newly discovered bacterium, called Brocadia anammoxidans and can be expressed as follows:

$$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O. \qquad (1.4)$$

Other processes are generally included in the nitrogen cycle, as (Sutton *et al*., 2011):

- ***Volatilization***. This process turns fertilizers and manures on the soil surface into gases like NH_3 , N_2O and N_2 that also join the atmospheric pool.
- ***Weathering of rocks***. The process where stored nitrogen in rocks is released by wind, rain and erosion.
- ***Runoff.*** This is process that carries the nitrogen in fertilizers and manure and the nitrogen in the soil into rivers and streams causing a concern for water quality.
- ***Leaching.*** The process that carries nitrates deep into the soil so that plants can no longer use them, producing a dual concern; for lost fertility and for water quality, as nitrates enter the groundwater and wells that provide drinking water.
- ***Dissimilatory nitrate reduction to ammonium (DNRA)***. This is an anaerobic respiration process, also called nitrate/nitrite ammonification. Microbes which undertake DNRA oxidize organic matter and use nitrate as an electron acceptor, reducing it to nitrite, then to ammonium. Both denitrifying and nitrate ammonification bacteria competes for nitrate in the environment, although DNRA acts to conserve bioavailable nitrogen as soluble ammonium rather than producing dinitrogen gas (Marchant *et al*., 2014).

1.3 Reactive Nitrogen

Reactive Nitrogen (N_r) is commonly defined as all nitrogen forms apart from N_2. This includes oxidized nitrogen forms, as NO, N_2O, NO_2, NO_3, reduced forms of nitrogen, as NH_4^+, NH_3, and organic nitrogen as proteins, amines, etc., with different states of oxidation.

The processes for the creation of reactive nitrogen starting from N_2 are described below, and are then is presented a quantification of reactive nitrogen flows between different ecosystems.

1.3.1 Processes for reactive nitrogen creation

The creation of reactive nitrogen occurs both through natural processes and through human interventions. Prior to the mid-19th century, the supply of reactive nitrogen to agricultural soils, either through biological nitrogen fixation, animal manure, or rotation of crops and fallow, supported human populations. However, by the end of the 1800s, with a growing human population, it became apparent that these sources of reactive nitrogen could not adequately support the needed expansion of agriculture. In the early 1900s, as the pressure for increased food production combined with the rising demand for nitrate to manufacture munitions due to the outbreak of World War I, a method was created in Germany by Fritz Haber and later improved and adapted to an industrial scale by Carl Bosch. Now known as the Haber-Bosch process, this method was the first to use high pressure to generate a chemical reaction that produced reactive forms of nitrogen, thus allowing for the mass production of fertilizer by synthesizing ammonia from nitrogen and hydrogen gases (Braun, 2007).

The Haber process combines nitrogen from the air with hydrogen derived mainly from natural gas (methane) into ammonia: the reaction, shown below, is reversible and the production of ammonia is exothermic ($\Delta H \sim -92$ kJ mol^{-1}):

$$\mathrm{N_2(g) + 3H_2(g) \Leftrightarrow 2NH_3(g)} \;\; ; \tag{1.5}$$

conversion is typically conducted at 15–25 MPa and between 400–500 °C, as nitrogen and hydrogen are passed over four beds of catalyst (typically based on iron promoted with K_2O, CaO, SiO_2, Al_2O_3) with cooling between each pass so as to maintain a reasonable equilibrium constant. On each pass only about 15% conversion occurs: the unreacted gases are recycled, and eventually an overall conversion of 97% is achieved (Elvers, 2011).

Nearly 100 years after its invention, the Haber-Bosch process remains the most economical anthropogenic means of fixing nitrogen and is responsible for sustaining nearly 40% of the current world population due to its ability to increase agricultural yields.

As the 20th century progressed, the annual rate of reactive nitrogen being produced continued to grow: it is estimated that, in the past 50–100 years, human activities have caused the global anthropogenic rate of nitrogen fixation to increase so that it is now ~2 times the natural rate of BNF in terrestrial ecosystems (Erisman *et al.*, 2011).

The chart reported in Figure 1.2 shows the global trends in N_r production. The graph depicts ammonia production for fertilizer and industry, total N_2 fixation, NO_x emissions from fossil fuel burning, together with global fossil fuel related CO_2 emissions and the world population. Several researches (eg. Erisman *et al.*, 2011; Singh and Bakshi, 2015; Xue *et al.*, 2016) deepened also the correlation between CO_2 emissions and N_r production, due to the similarity between the drivers (food, feed and energy) and, to some extent, the sources. In particular is noted that the strong correlation between nitrogen enrichment and climate change at a source level comes from the fact that nitrogen is the key parameter allowing sustaining a growing world population with its increasing demand for energy from fossil fuels (Erisman *et al.*, 2011).

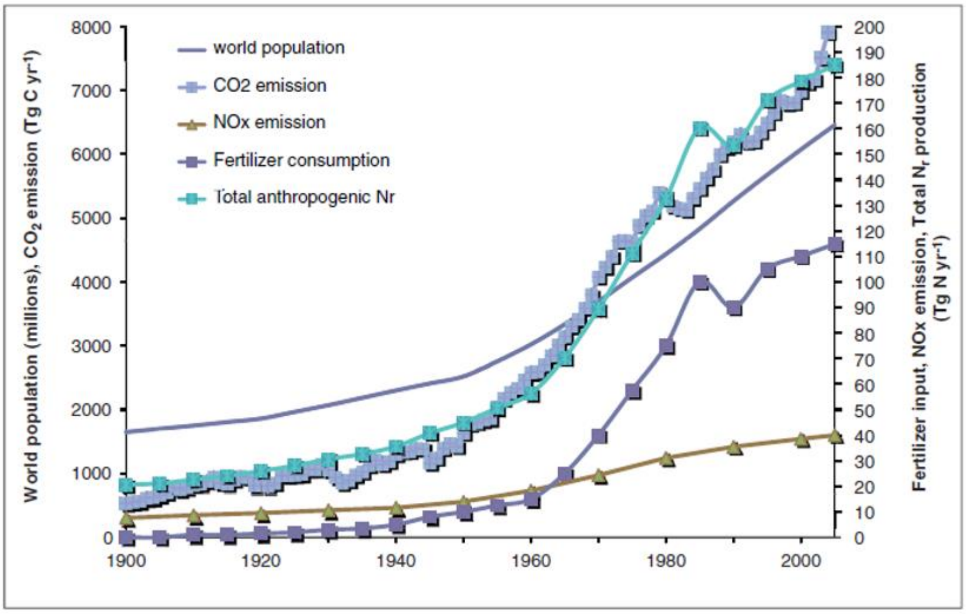


Figure 1.2. *Global trends in human population, CO_2 emissions [Tg Cyr^{-1}] and total anthropogenic reactive nitrogen production [Tg Nyr^{-1}] throughout the 20th century. The graph also includes average fertilizer production and the increase in NO_x emissions from fossil fuel burning. Source: Erisman* et al.*, 2011.*

The processes that generate reactive nitrogen, divided into natural and anthropogenic processes, are summarized as follows.

Under ***natural conditions***, the breaking of the triple bond that binds two nitrogen atoms together as N_2 can derive from:

- ***volcanic activity,*** specifically hot magmatic vents that offer the opportunity for atmospheric nitrogen to be rapidly heated and to undergo thermally catalyzed reactions producing mainly oxides of nitrogen (Mather *et al.*, 2004), although volcanoes also emit reduced forms (Galloway *et al.*, 2003; Schlesinger, 2009).
- ***lightning,*** that produce NO and NO_2 in the atmosphere (Drapcho *et al.*, 1967).

- ***activity of microbes,*** able to carry out the process known as Biological Nitrogen Fixation (BNF). These microbes are generally bacteria often residing in a symbiotic relationship with certain legumes, including soybeans, and many native plants in the legume family. In the oceans, BNF is carried out primarily by cyanobacteria, commonly known as blue-green algae (Braun, 2007).
- ***weathering of rocks,*** attributable to the content of nitrogen in rock that originates as organically bound nitrogen associated with sediment, or in thermal waters representing a mixture of sedimentary, mantle, and meteoric sources of nitrogen (Holloway and Dahlgren, 2002).

In addition, senescence of plants, wildlife and forest fires are natural processes that can be accounted in the reactive nitrogen balance, but their contribution results only in the redistribution of reactive nitrogen in the biosphere, rather than in its creation.

Anthropogenic activities enhancing the formation of N_r can be synthesized as follows:

- ***combustion of fossil fuels*** for energy production, which generates nitrogen oxides from the oxidation of N_2 or fossil organic N in the fuel;
- ***production of fertilizers and chemicals*** (e.g. nylon, explosives), mainly through the Haber–Bosch process, which creates NH_3 by the reaction of N_2 and H_2;
- ***agroecosystems activities,*** such as planting of nitrogen-fixing crops (e.g. legumes) which convert N_2 to NH_3 incorporated in the organic matter.

1.3.2 Quantification of reactive nitrogen flows

It is very difficult to make accurate estimates of the flows associated with the creation of reactive nitrogen and its transfer into the various ecosystems.

An exhaustive bibliography of research published from the 90's until 2004 is the one proposed by Galloway *et al*. (2004) in which reference is made to papers that addressed the nitrogen cycle on a global and regional scale, the major components of the nitrogen cycle (food production, fertilizer production, fossil fuel combustion, industrial uses of reactive nitrogen, atmosphere, Biological Nitrogen Fixation) and the relationship to public policy.

It is proposed below a summary of the literature data relating to the creation of reactive nitrogen, referring to both the main natural processes (lighting and biological nitrogen fixation) and the human intervention.

- ***Nitrogen fixation by lighting***. High temperatures occurring in lightning strikes produce NO in the atmosphere from molecular oxygen and nitrogen. Subsequently this NO is oxidized to NO_2

and then to HNO_3 and quickly (i.e., days) removed by wet and dry deposition thus introducing N_r into ecosystems primarily over tropical continents. Most current estimates of N_r creation by lightning range between 3 and 10 Tg Nyr^{-1} (Ehhalt *et al.*, 2001). Although this amount is small relative to terrestrial BNF, it can be important for regions that do not have other significant N_r sources. It is also important because it creates NO_x high in the free troposphere compared to NO_x emitted at the earth's surface. As a result, it has a longer atmospheric residence time and is more likely to contribute to tropospheric O_3 formation, which significantly impacts the oxidizing capacity of the atmosphere (Galloway *et al*., 2004).

- ***Biological Nitrogen Fixation (BNF).*** Quantifying the magnitude of natural terrestrial N_r creation by BNF is tenuous owing most notably to uncertainty and variability in the estimates of rates of BNF at the plot scale. Specifically, methodological differences, uncertainties in spatial coverage of important N-fixing species, and locational biases in the study of BNF all suggest critical gaps in understanding of natural BNF at large scales (Cleveland *et al.* 1999). In addition, for many large areas where BNF is likely to be important, particularly in the tropical regions of Asia, Africa, and South America, there are virtually no data on natural terrestrial rates of BNF. An annual global BNF contribute between 100 and 290 Tg Nyr^{-1} to natural terrestrial ecosystems prior to large-scale human disturbance was estimated (Galloway *et al*., 2004).
- ***Anthropogenic reactive nitrogen.*** From the middle of the 19th century to the end of the 20th century, the world's population increased ~4.5-fold, from 1.3 to 5.8 billion. Cultivation-induced N_r creation increased by only ~2-fold from ~15 Tg Nyr^{-1} in 1860 to ~33 Tg Ny^{-1} in the mid-1990s (Smil, 1999). Symbiotic BNF by Rhizobium associated with seed legumes resulted in 10 Tg Nyr^{-1} (8–12 Tg Nyr^{-1}) of new nitrogen. Biofixation by leguminous cover crops (forages and green manures such as clover, alfalfa, vetches) accounted for an additional 12 Tg Nyr^{-1} (10–14 Tg Nyr^{-1}) of new nitrogen. As Smil noted, biofixation by non-Rhizobium nitrogen-fixing species was of less importance, fixing on the order of 4Tg Nyr^{-1} (2–6 Tg Nyr^{-1}). Cyanobacteria fixed on the order of 4–6 Tg Nyr^{-1} in wet-rice fields, while endophytic N-fixing organisms in sugar cane fixed an additional 1–3 Tg Nyr^{-1}. The global total from cultivation is thus ~33 Tg Nyr^{-1} within a range of 25–41 Tg Nyr^{-1} (Smil 1999). Applying Smil's crop-specific mean fixation rates to the crop area data on a regional basis from FAO (2002), Galloway *et al.* (2004) estimated that for 1995 that total global C-BNF was 31.5 Tg Nyr^{-1}, very similar to Smil's value of 33 Tg Nyr^{-1}. Relative to cultivation-induced BNF, about three times as much N_r was created with the Haber-Bosch process. In 1995, 100 Tg N of NH_3 was created for food production and other industrial activities.

Of this amount, about 86% (~86 Tg Ny^{-1}) was used to make fertilizers. The remaining 14 Tg Nyr^{-1} was dispersed to the environment during processing or used in the manufacture of synthetic fibers, refrigerants, explosives, plastics, rocket fuels, nitroparaffins, etc. (Smil, 1999; Domene and Ayres, 2001). As with the production of fertilizer, this also represents creation of new N_r that is introduced into environmental systems. The increase in energy production by fossil fuels resulted in increased NO_x emissions from 0.3 Tg Nyr^{-1} in 1860 to ~24.5 Tg Nyr^{-1} in the early 1990s. (Galloway *et al*., 2004).

Several studies have also been carried out to quantify the reactive nitrogen distribution via atmospheric and hydrologic pathways, providing a context to evaluate the extent to which human intervention in the nitrogen cycle has substantially changed the nitrogen distribution on a global and regional basis.

A synthesis that proposes a global reference model was made by Galloway *et al*. (2004) in which it is noted that, from the middle of the 19th century to the end of the 20th century, the amount of N_r created by natural terrestrial processes decreased by ~15% (120 to ~107 Tg Nyr^{-1}), while N_r creation by anthropogenic processes increased by ~10-fold (~15 to ~156 Tg Nyr^{-1}), and it is stressed that much of the N_r created was dispersed to the environment.

With reference to the estimates for the early 1990s, Galloway *et al*. (2004) pointed out that, of the ~268 Tg Nyr^{-1} created by natural terrestrial and anthropogenic processes, ~98 Tg Nyr^{-1} of NO_x and NH_3 was emitted to the atmosphere. Of that amount, ~65 Tg Nyr^{-1} was deposited back to continents and ~33 Tg Nyr^{-1} was deposited either to the estuary and shelf region (~8Tg Nyr^{-1}) or to the open ocean (~25 Tg Nyr^{-1}). An additional ~59 Tg Nyr^{-1} was injected into inland (11 Tg Nyr^{-1}) and coastal (48 Tg Nyr^{-1}) systems via rivers. Thus, losses of N_r from continents to the marine environment were estimated as ~81 Tg Nyr^{-1} from atmospheric and riverine transport. According to research results, rivers are considered more important than atmospheric deposition in delivering N_r to coastal/shelf regions (~48 Tg Nyr^{-1} versus ~8Tg Nyr^{-1}, respectively). Conversely, since most of the N_r introduced to coastal systems is converted to N_2 along the continental margins, the atmosphere is more important than rivers in delivering N_r to the open ocean.

Always according to the estimates of Galloway *et al*. (2004) a small (~11 Tg Nyr^{-1}), yet environmentally important, amount of the N_r created, in the early 1990s, is emitted to the atmosphere as N_2O from continents, estuaries, and the shelf region, where a portion (~25%) accumulates in the troposphere until eventual destruction in the stratosphere. Thus, of the ~268 Tg Nyr^{-1} of new N_r that entered continents, ~81 Tg Nyr^{-1} was transferred to the marine environment via atmospheric and riverine transport and ~12 Tg Nyr^{-1} was emitted to the atmosphere as N_2O. Of the remaining 175 Tg Nyr^{-1} of N_r was estimated that ~115 Tg Nyr^{-1} is converted to N_2 and that ~60 Tg Nyr^{-1} is accumulating in terrestrial systems.

The above data regarding the creation of reactive nitrogen and the its flows between the different environmental compartments are represented in the Figure 1.3.

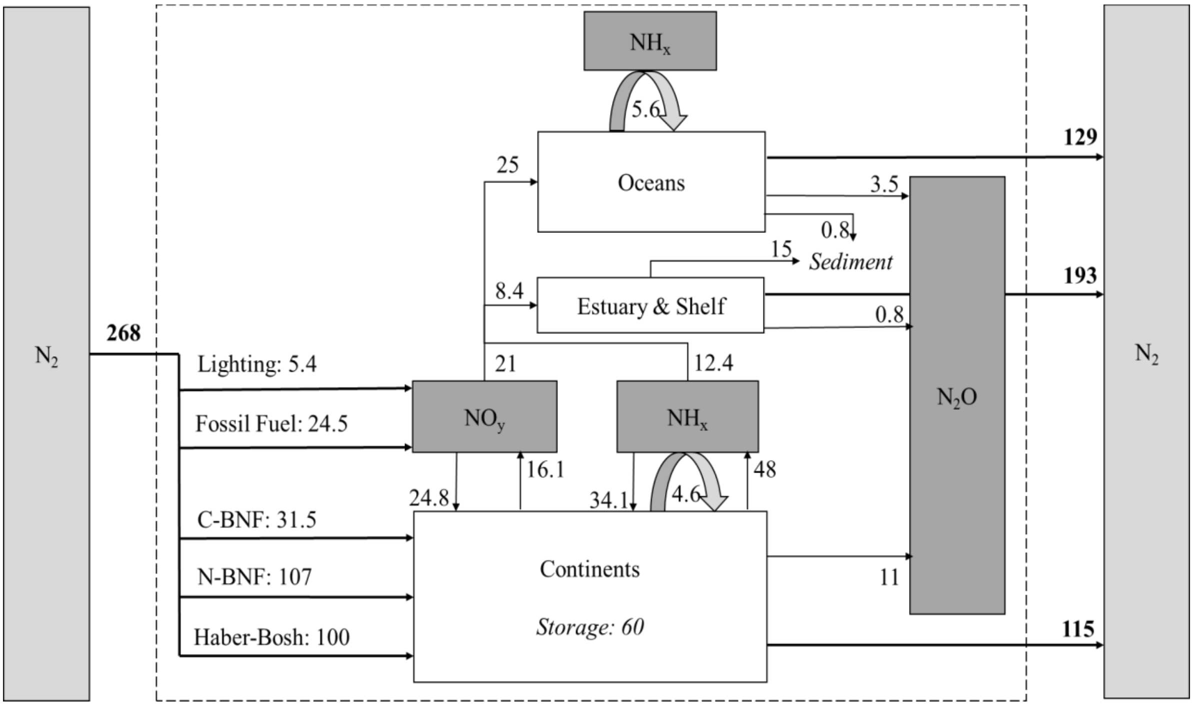


Figure 1.3. *Creation and flow of reactive nitrogen between environmental compartments for the early 1990s [Tg Nyr^{-1}]. All shaded boxes represent reservoirs of nitrogen species in the atmosphere. Creation of N_r is depicted with bold arrows from the N_2 reservoir to the N_r reservoir (depicted by the dotted box). 'N-BNF' is biological nitrogen fixation within natural ecosystems, 'C-BNF' is biological nitrogen fixation within agroecosystems. Denitrification creation of N_2 from N_r within the dotted box is also shown with bold arrows. All arrows that do not leave the dotted box represent inter-reservoir exchanges of N_r. The dashed arrows within the dotted box associated with NH_x represent natural emissions of NH_3 that are re-deposited on fast time-scales to the oceans and continents. Adapted from Galloway et al. (2004).*

In addition to the above reported with reference to the early 1990s, the research of Galloway *et al*. (2004) also produced an estimate of reactive nitrogen streams in the mid-1800s, reference year 1860, and a projection to 2050 in order to provide an indication of the trend of data related to the nitrogen budget. A summary of the estimates made is reported in the Table 1.1 with reference to the three time horizons.

Table 1.1. *Global reactive nitrogen creation and distribution [Tg N yr^{-1}] for three different reference time horizons. Adapted from Galloway et al. (2004).*

	1860	**Early 1990s**	**2050**
N_r creation			
Natural			
Lighting	5.4	5.4	5.4
BNF-terestrial	120.0	107.0	98.0
BNF-marine	121.0	121.0	121.0
Subtotal	246.0	233.0	224.0
Anthropogenic			
Haber-Bosch	0	100.0	165.0
BNF-cultivation	15.0	31.5	50.0
Fossil fuel combustion	0.3	24.5	52.2
Subtotal	15.0	156.0	267.0
Total	*262.0*	*389.0*	*492.0*
Atmospheric emission			
NO_x			
Fossil fuel combustion	0.3	24.5	52.2
Lightning	5.4	5.4	5.4
Other emissions	7.4	16.1	23.9
NH_3			
Terrestrial	14.9	52.6	113.0
Marine	5.6	5.6	5.6
N_2O			
Terrestrial	8.1	10.9	13.1 ±?
Marine	3.9	4.3	5.1
Total (NO_x and NH_3)	*13.1*	*46.0*	*82.0*
Atmospheric deposition NO_y			
Terrestrial	6.6	24.8	42.2
Marine	6.2	21.0	36.3
Subtotal	12.8	45.8	78.5
NH_x			
Terrestrial	10.8	38.7	83
Marine	8.0	18.0	33.1
Subtotal	18.8	56.7	116.1
Total	*31.6*	*103.0*	*195.0*
Riverine fluxes			
N_r input into rivers	69.8	118.1	149.8
N_r export to inland systems	7.9	11.3	11.7
N_r export to coastal areas	27.0	47.8	63.2
Denitrification			
Continental			
Terrestrial		67.0	95.0
Riverine		47.8	63.2
Subtotal	98.0	115.0	158.0
Estuary and shelf			
Riverine nitrate	27.0	47.8	63.2
Open ocean nitrate	145.0	145.0	145.0
Subtotal	172.0	193.0	208.0
Open ocean	129.0	129.0	129.0

Data give an indication of the expected evolution, especially in relation to the creation of reactive nitrogen by human activity: the analysis shows a forecast of more than 70% increase by 2050 of anthropogenic reactive nitrogen creation, while remaining stable the creation by natural way.
A synthesis of the analysis of the historical trend of creation is that made by Galloway *et al*. (2014), starting from the research of Erisman *et al*. (2011), who, for quantification, chose a per-capita approach, instead of global one, and distinguished three eras of N_r creation, as follows:

- The first era ended in 1950. Over the period 1850–1950, N_r creation increased roughly proportional to the population; per-capita N_r creation was constant at ∼12 kg Nyr^{-1}.
- The second era (1950 to ∼1980) was a period of a rapid increase in per-capita N_r creation. It rose from ∼12 kg Nyr^{-1} in 1950 to ∼30 kg Nyr^{-1} in 1980; at the same time, the global population continued to increase, pointing towards an even greater increase in total N_r creation. Reasons were the increasing use of fossil fuel energy and increased use of Haber–Bosch fertilizer with a decreasing use efficiency in support of the consumption of higher quality food, especially animal protein, while ignoring the nitrogen use efficiency.
- The third era (approximately 1980 to current) of the global per capita N_r creation reached a new equilibrium between population growth and N_r creation where the per-capita N_r creation remained at ∼30 kg Nyr^{-1} over this ∼20 yr period and again, just like in the first period, N_r creation kept pace with population growth. Since the population growth now is much faster than in the first period so is N_r production. Total N_r creation continues to rise with an increasing global population. The stability in the overall per-capita N_r creation, relative to the previous ∼20 yr, is remarkable, as it is a result of many individual underlying processes. The emissions from fossil fuel combustion decreased over the last few decades, due to efficient NO_x controls in many developed countries. In part due to increase in the nitrogen use efficiency of agricultural production as a result of environmental considerations, but also due to the cost of fertilizer activities, e.g., in OECD countries. The economic turnover in Eastern Europe also meant a strong decrease in fertilizer use and associated wastage in that part of the world. On the other hand, production of corn for biofuel, the strong increase in meat production and especially change in diets in large parts of the developing world caused significant increases in fertilizer use.

Worthy of note is also the analysis concerning the spatial heterogeneity of reactive nitrogen creation and distribution. In this regard, from the research of Galloway *et al*. (2004), emerges that overall, Asia, Europe, and North America account for nearly 90% of the current human increase in biological nitrogen fixation and use; thus the majority of the current focus on problems associated with an accelerated nitrogen cycle should be on these regions. However, substantial increases are projected over the next 50 years for other regions of the world. As for the already heavily changed continents, it is essential to improve the understanding of the potential fates for additional nitrogen in these future hotspots. This statement is especially true for tropical regions, where nitrogen often is not the limiting nutrient even in little disturbed ecosystems (Martinelli *et al.*, 1999). This fact, combined with warm, often wet climates, can lead to high rates of nitrogen loss to atmospheric and aquatic realms, making it likely that even a modest rise in anthropogenic nitrogen inputs could lead to rapid increases in reactive nitrogen losses to air and water (Matson *et al.*, 1999).

With reference to the above mentioned data related to reactive nitrogen flows, it should be noted that the researchers agree that there is large uncertainty about the estimates related to storage and N_2 production via denitrification, and improved resolution of the partitioning of anthropogenic N_r is considered as a critical research priority. According to *Galloway et al*. (2004), the biggest unknown in the nitrogen cycle, in managed and unmanaged ecosystems, is the rate of denitrification and its relationship to reactive nitrogen creation rates and ecosystem characteristics that control N_r cycling and storage. Until a more complete understanding of the magnitude of nitrogen losses in managed and unmanaged ecosystems is gained, determining the true, ultimate fate and long-term impact of reactive nitrogen created by human actions will remain an important but unanswered scientific question.

1.4 The effects of nitrogen on the environment

An interesting starting point for introducing the theme of the relation between nitrogen and the environment is the concept of planetary boundary, an approach that aims to define a safe operating space for human societies to develop and thrive, based the evolving understanding of the functioning and resilience of the Earth system. Since its introduction, the framework has been subject to scientific scrutiny and has attracted considerable interest and discussions within the policy, governance, and business sectors as an approach to inform efforts toward global sustainability. (Steffen *et al*., 2015).

As can be seen from the Figure 1.4, the limit defined for the planetary boundary in relation to the nitrogen cycle is one of those which are today exceeded. The control variable for this indicator is defined as the “industrial and intentional biological fixation of N” and its current value is estimated at ~150 Tg N yr^{-1} compared to an estimated planetary boundary equal to 62 Tg N yr^{-1}.

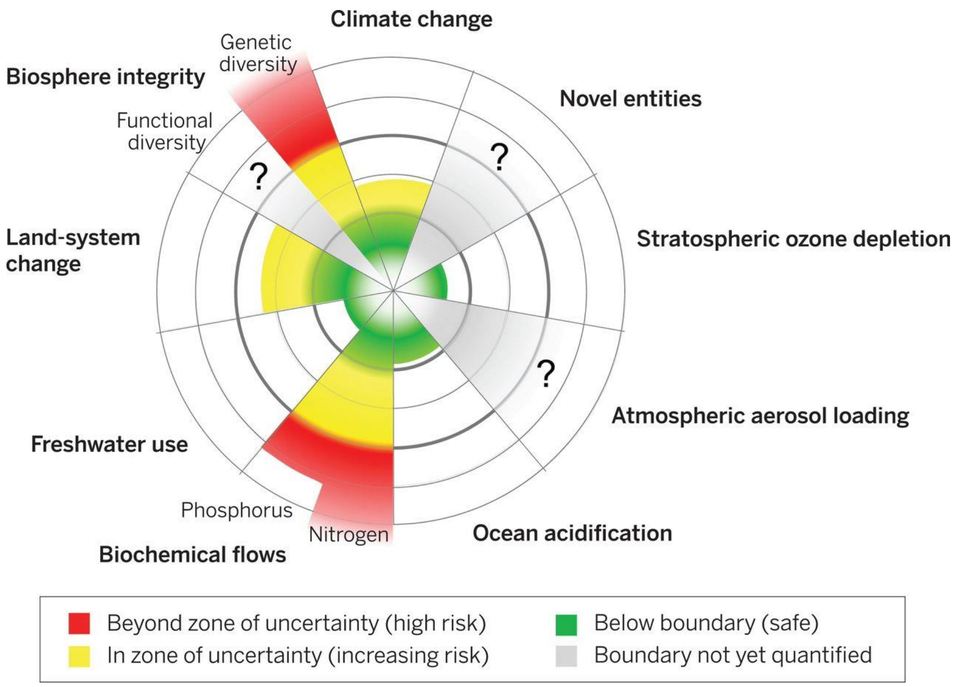


Figure 1.4. *Current status of the control variables for seven of the nine planetary boundaries. The green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The planetary boundary itself lies at the inner heavy circle. The control variables have been normalized for the zone of uncertainty (between the two heavy circles); the center of the figure therefore does not represent values of 0 for the control variables. The control variable shown for climate change is atmospheric* CO_2 *concentration. Processes for which global-level boundaries cannot yet be quantified are represented by gray wedges; these are atmospheric aerosol loading, novel entities, and the functional role of biosphere integrity. (Steffen et al., 2015).*

Nature and biodiversity could only exist because of the availability of reactive nitrogen provided by limited natural sources such as lightning, biomass burning and biological nitrogen fixation. Because of the limited availability, nature became very effective in conserving and re-using reactive nitrogen compounds.

Nitrogen, together with other nutrients and water, is the limiting factor for the production of food. Humankind has sought for different ways to increase the crop production necessary for food to sustain a growing population, leading to the development of synthetic fertilizer production based on the Haber–Bosch process.

This additional availability of reactive nitrogen has led to increased crop production and to the intensification of agriculture: according to different research, the large increase in population is due to intensification and extension of agricultural land, but also due to the availability of fertilizers. An estimate of the current human population supported by synthetic fertilizer is 48%, 100 years after the invention of the synthesis of ammonia from its elements (Smil, 1997; Erisman *et al.*, 2008), as shown in the Figure 1.5.

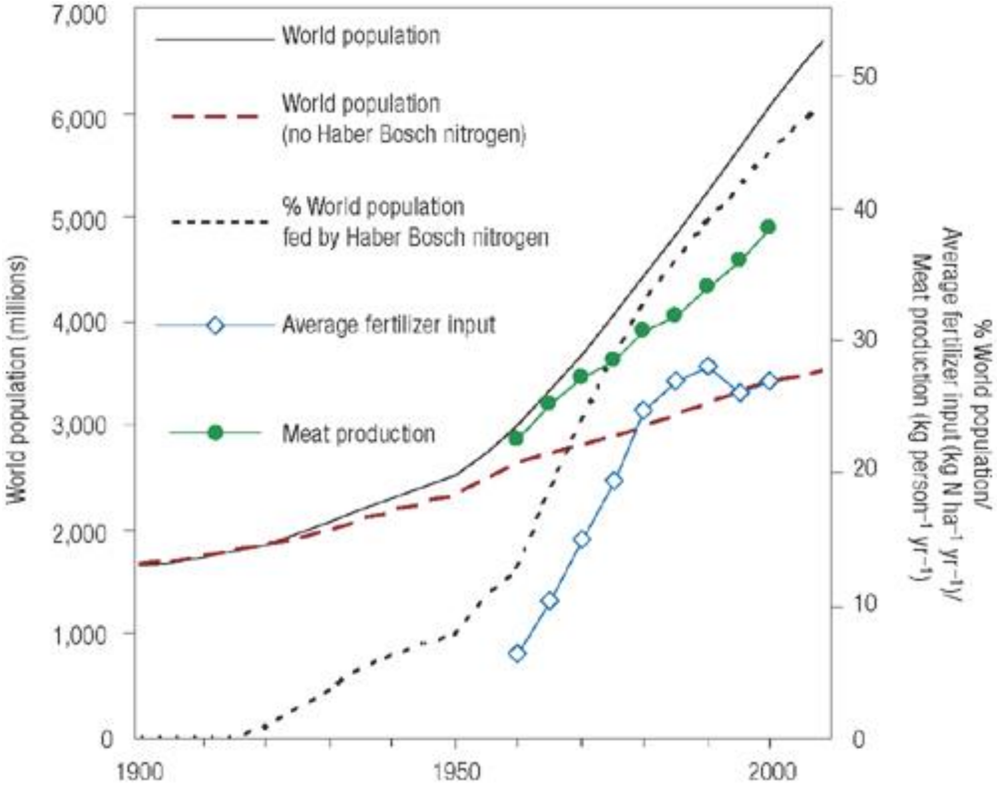


Figure 1.5. *Trends in human population and nitrogen use throughout the twentieth century. Of the total world population (solid line), an estimate is made of the number of people that could be sustained without reactive nitrogen from the Haber–Bosch process (long dashed line), also expressed as a percentage of the global population (short dashed line). The recorded increase in average fertilizer use per hectare of agricultural land (blue symbols) and the increase in per capita meat production (green symbols) is also shown. Source: Erisman et al. (2008).*

To maximize crop production, the availability of cheap fertilizer in the industrialized world led to excessive use of nitrogen, resulting in a large nitrogen surplus and increased nitrogen losses. As the use of fossil fuel in the industrial revolution expanded, fertilizer production increased similarly (see Figure 2.1). The industrial revolution was accelerated by the combustion of fossil fuels producing heat and power, but also polluting gases, such as carbon dioxide, sulphur dioxide and nitrogen oxides. The use of fossil fuels led at the same time to an increase in the production of fertilizer through the Haber–Bosch process, and to a replacement of manpower by machines increasing the productivity and yield per hectare, further accelerating excess nitrogen. Furthermore, the availability of fossil fuels made globalization possible, transporting food, feed, goods and products all over the world, and depleting nutrients in one area and concentrating nutrients in another area, e.g. in intensive livestock production (Galloway *et al* .,2008). These leakages from agriculture, industry and transport, in their turn, have led to a cascade of nitrogen through the global environment causing a number of different environmental effects: loss of biodiversity, eutrophication of waters and soils, drinking water pollution, acidification, greenhouse gas emissions, human health risks through exposure to oxidized nitrogen, ozone and particulates, and depletion of the ozone layer (Sutton *et al*., 2011).

On a global scale, the need for nitrogen management has been formulated in the 2004 Nanjing Declaration, which was presented to the United Nations Environment Programme (UNEP) in Nanjing, China on October 2004. With the aim to optimize nitrogen management in food and energy production on a local, regional and global scale, the declaration calls upon the national governments for instance to:

- support the further assessment of the nitrogen cycle,
- focus efforts on increasing the efficiency and effectiveness of agricultural production and energy use, while decreasing the adverse effects of reactive nitrogen, and
- take action to enhance the availability of reactive nitrogen as food, fiber and other basic needs in regions of nitrogen deficiency and avoid nitrogen pollution.

From what has been presented in the preceding sections, it is clear that any strategy for the management of the issues related to the nitrogen cycle, at national or global level, should start from an understanding of the benefits and adverse effects on humans and ecosystems related to the use of reactive nitrogen in its various forms: these aspects are summarized in the following paragraphs.

1.4.1 Benefits of reactive nitrogen

Nitrogen is an essential component of many compounds found in living cells within plants, animals and humans. All nitrogen in animals and humans originates in one way or another from plants or microbes because only they have the ability to convert mineral forms of reactive nitrogen, such as nitrate and ammonium, into organic nitrogenous compounds such as amino acids and nucleotides, which are the building blocks of proteins and nucleic acids essential for life. The availability of these basic mineral forms of N_r is a key factor determining the productivity of crops for food, feed, fibre and bio-energy and hence for all human activities (Sutton *et al*., 2011).

The provision of reactive nitrogen through mineral fertilizers has contributed greatly to the increased production of agricultural products needed to feed the increasing global population (Erisman *et al*., 2008) and hence to food security. In 1900, world agriculture was able to sustain around 1.6 billion people on 850 million ha of agricultural land using mainly extensive cultivation practices without mineral fertilizers. The same combination of agronomic practices extended to today’s 1.5 billion ha cropland would feed around 3 billion people, i.e. no more than around 50% of the present population at the generally inadequate per capita level of year 1900 diets.

In this sense, the use of reactive nitrogen provides huge benefits for humankind, but in order to maximize these benefits (broadly intended, including economic as well as social, health and political values) the efficiency of use of nitrogen inputs should be optimized.

For the major cereal food crop in Europe, wheat, it can be estimated that the agronomic benefit obtained by application of nitrogen based fertilizer amounts to a yield increase from 86 to 150 million tons of grain per year (Sutton *et al*., 2011), based on an average yield without mineral nitrogen fertilizer in ecological farming at 60%–70% of yield with mineral N fertilizer (Offermann and Nieberg, 2000).

Fertilizer nitrogen has also played a beneficial role in avoiding natural terrestrial ecosystems from being converted to cropping systems (Tilman *et al*., 2002). At the global scale, land use changes due to replacement of forest or natural grasslands with agricultural cropland contribute significantly (6%–17%) to greenhouse gas emissions because large amounts of carbon dioxide fixed or stored in soil organic matter are released upon cultivation. In comparison, the greenhouse gas emissions from production and use of mineral fertilizers are relatively small, constituting 0.8% and 1.3%, respectively. The estimated contribution of European agriculture to total greenhouse gas emissions is only around 10% and land use changes in Europe have been estimated to act as a net sink for greenhouse gases (Sutton *et al*., 2011). However, this is solely driven by afforestation, with cropped land being a small net source of CO_2, although at a declining rate.

If less intensified agriculture becomes predominant in Europe, implying significantly lower or completely abandoning nitrogen fertilization, it may result in land use changes either within Europe or elsewhere in the world to compensate for the decrease in crop yields. Thus, some authors as Von Witzke and Noleppa (2010) demonstrated that increasing production of agricultural commodities in the EU would significantly reduce the current EU net food imports which have increased over the past decades, and hence also the associated import of ‘virtual land use’ around the world. From the same point of view, agricultural intensification may be viewed as a greenhouse gas mitigation mechanism and a measure for preserving natural habitats (Balmford *et al*., 2005). Other authors (eg. Rudel *et al*., 2009) investigated also the trends in crop yields and cultivated land areas for ten global regions during the period 1990–2005, finding that agricultural intensification was not generally accompanied by a decline or stasis in cropland area at a national scale.

However, some researchers raised doubt (eg. Tilman *et al.*, 2002) that avoiding new cultivation of major areas of native land is crucial with respect to reducing the anticipated increase in atmospheric CO_2 levels originating from land use change. Economically and environmentally, sound nitrogen fertilization practices on the generally fertile and productive soils in the majority of European countries can contribute to this (Brentrup and Pallière, 2008) even if other factors will also play a significant role.

The pressure on native land may also be accentuated with the increased focus on replacing fossil energy with energy generated by biomass. The land area required to meet the EU target for bio-ethanol in vehicle fuels by 2020 (10% blending by volume, total consumption 101 million t gasoline) would be 9.5 million ha if optimally fertilized wheat was the source, but 16.7 million ha (out of a total arable area of 98 million ha) if not fertilized with nitrogen, supposing 60%–70% yield reduction. Extensification of agricultural production in Europe, in parallel with an increased European demand for bioenergy, may thus increase the pressure on land resources elsewhere in the world.

Fertilizer nitrogen inputs also affect the level of soil organic matter (SOM), albeit only in a long-term perspective and often relatively moderately (Raun *et al.*, 1998). Soil organic matter is one of the most important factors for soil fertility. This is the case because soil organic matter directly affects nutrient availability via mineralization of organically bound nitrogen, phosphorus and sulfur, via adsorption of cations and via complexation of trace elements. In addition, soil organic matter indirectly affects soil water dynamics, stability of soil aggregates, resilience against erosion and other deterioration processes (Sutton *et al.*, 2011).

Appropriate nitrogen inputs contribute significantly to maximizing the utilization of other costly inputs or resources for soil and crop management such as other nutrients, pesticides, labour, energy and capital as well as crop genetic potential (cultivars). Interactions between genetic potential, N, P and K application were studied, among the others, by Johnston and Poulton (2009) who demonstrated that the nitrogen application clearly interacts with phosphorus application, resulting in larger nitrogen use efficiency when phosphorus was also applied.

Finally, benefits of nitrogen also emerge via the very important use of nitrogen products in the manufacture of explosives, nylon and acrylic fibers, methacrylate and other plastics, foamed insulation and plastics, electronics, metal plating, gold mining, animal feed supplements, herbicides, and many pharmaceuticals (Maxwell, 2004). Other uses of reactive nitrogen compounds involve ammonia for the abatement of atmospheric NO_x and SO_2 emissions as well as a refrigerant for cooling, especially in connection with food storage. Ammonium-phosphates and ammonium-sulphates are components of metallurgy for welding and firefighting. Despite these important applications, the consumption of reactive nitrogen for industrial use only constitutes around one third of the total European budget, the dominating uses being crop and livestock production (Sutton *et al*., 2011).

1.4.2 Negative effects of reactive nitrogen

Besides the benefits of the use of nitrogen compounds, as described in the previous paragraph, must be taken into account that nitrogen, in its various chemical forms, plays a major role in a great number of environmental issues. It contributes to acidification and eutrophication of soil, groundwater and surface waters, decreasing ecosystem vitality and biodiversity and causing groundwater pollution through nitrate leaching. Nitrogen compounds give a contribution to carbon sequestration, global climate change, and formation of ozone, oxidants and aerosols, potentially posing a threat to human health and affecting visibility. Each of the emissions takes part in the cycling of nitrogen causing a number of different effects with its consequent linkages.

In principle, every pollutant can cause a cascade of effects; however, nitrogen stands out, because it can occur in many very mobile compounds that can cause a wide range of effects. For example, reactive nitrogen emitted to the atmosphere from fossil fuel combustion, in sequence can cause increasing of tropospheric ozone levels and atmospheric acidity and decreasing of visibility. Once deposited from the atmosphere, reactive nitrogen compounds can acidify soils and waters, over-fertilize forests, grassland and coastal ecosystems, and can then be re-emitted to the atmosphere as nitrous oxide contributing to global warming and stratospheric ozone depletion. The environmental changes will continue as long as N_r remains in circulation, for reactive nitrogen once created, and then lost to the environment, can be transported to any part of the Earth system. This sequence of effects has been termed the nitrogen cascade (see Figure 1.6).

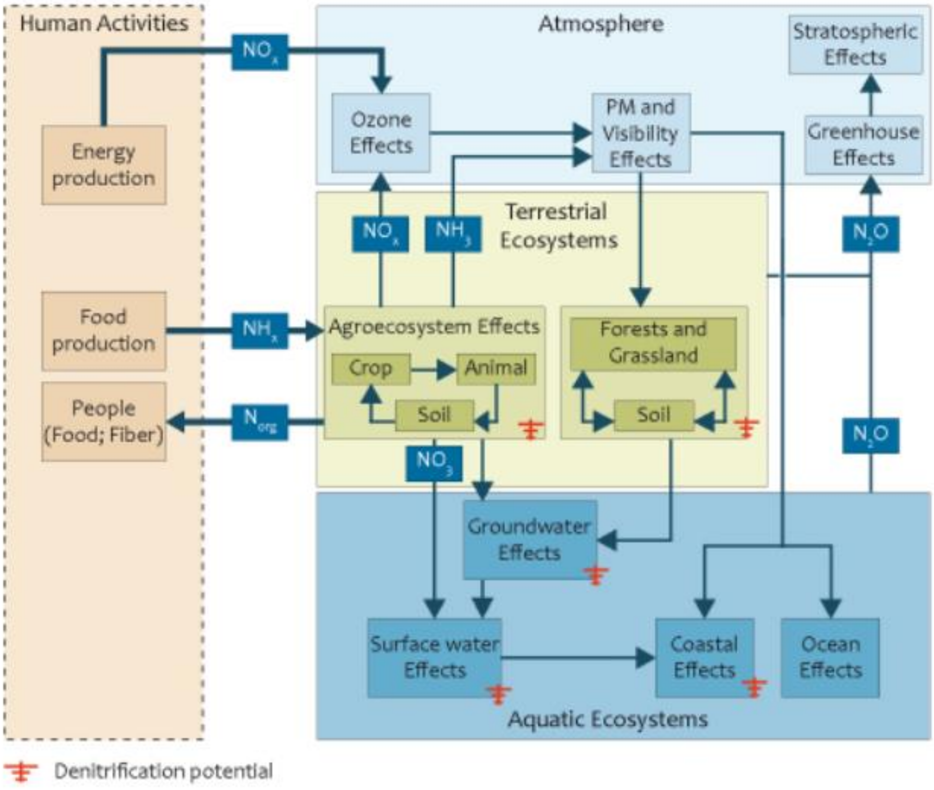


Figure 1.6. *Illustration of the nitrogen cascade showing the sequential effects that nitrogen can have in various reservoirs after it has been converted from a nonreactive to a reactive form. Adapted from Galloway et al. (2003).*

While some environmental problems are strictly local, like soil and ground water pollution or exposure to high concentrations, nitrogen-related problems include the regional to global scales. The emissions of N_2O readily spread across the atmosphere and give a contribution to global warming. NO_x has a continental character and can be transported over long distances between continents; to a lesser extent; NH_3 has also a continental character, but smaller intercontinental exchange. The scale of nitrogen problems in estuaries and coastal seas, instead, is linked to the extent of the river basin feeding them (Sutton *et al*., 2011).

1.4.2.1 Climate change

As reported by IPCC (see Pachauri *et al*, 2014), climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer.

The Earth's climate system is powered by solar radiation. Approximately half of the energy from the sun is supplied in the visible part of the electromagnetic spectrum. As the earth's temperature has been relatively constant over many centuries, the incoming solar energy must be nearly in balance with outgoing radiation. Of the incoming solar shortwave radiation (SWR), about half is absorbed by the earth's surface. The fraction of SWR reflected back to space by gases and aerosols, clouds and by the earth's surface (albedo) is approximately 30%, and about 20% is absorbed in the atmosphere. Based on the temperature of the earth's surface the majority of the outgoing energy flux from the earth is in the infrared part of the spectrum. The longwave radiation (LWR, also referred to as infrared radiation) emitted from the earth's surface is largely absorbed by certain atmospheric constituents – water vapour, carbon dioxide, methane, nitrous oxide and other greenhouse gases (GHGs) – and clouds, which themselves emit LWR into all directions. The downward directed component of this LWR adds heat to the lower layers of the atmosphere and to the earth's surface (greenhouse effect). The main identified drivers of climate change are represented in the following Figure 1.7.

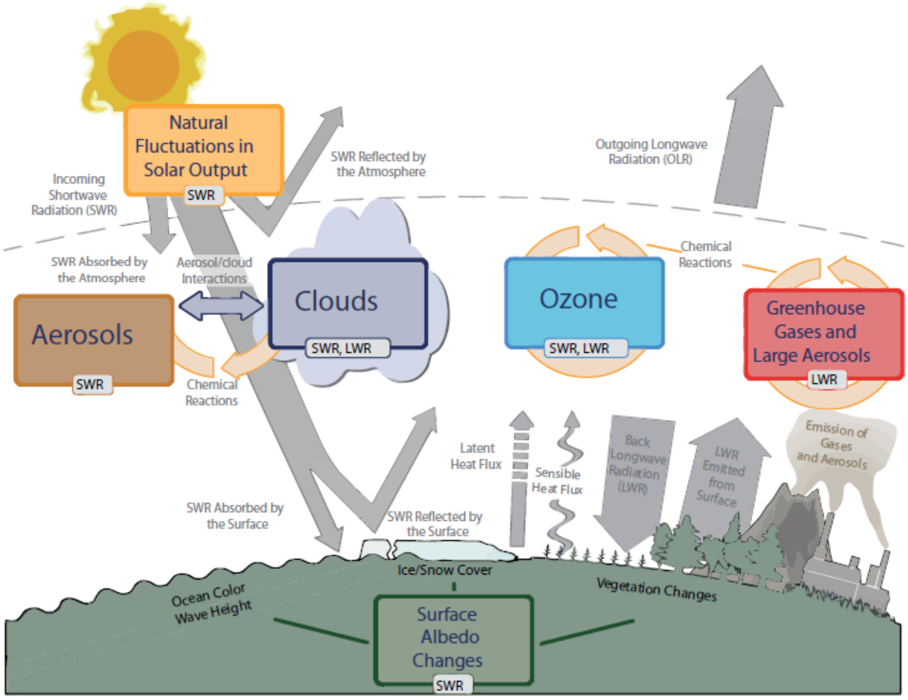


Figure 1.7. *Main drivers of climate change. The radiative balance between incoming solar shortwave radiation (SWR) and outgoing longwave radiation (OLR) is influenced by global climate 'drivers'. Natural fluctuations in solar output (solar cycles) can cause changes in the energy balance (through fluctuations in the amount of incoming SWR). Human activity changes the emissions of gases and aerosols, which are involved in atmospheric chemical reactions, resulting in modified* O_3 *and aerosol amounts.* O_3 *and aerosol particles absorb, scatter and reflect SWR, changing the energy balance. Some aerosols act as cloud condensation nuclei modifying the properties of cloud droplets and possibly affecting precipitation. Anthropogenic changes in GHGs and large aerosols (>2.5* μ*m in size) modify the amount of outgoing LWR by absorbing outgoing LWR and re-emitting less energy at a lower temperature. Surface albedo is changed by changes in vegetation or land surface properties, snow or ice cover and ocean colour. These changes are driven by natural seasonal and diurnal changes (e.g., snow cover), as well as human influence (e.g., changes in vegetation types) (Forster et al., 2007).*

Changes in the global energy budget derive from either changes in the net incoming solar radiation or changes in the outgoing longwave radiation. Changes in the net incoming solar radiation derive from changes in the sun's output of energy or changes in the earth's albedo. Reliable measurements of total solar irradiance (TSI) can be made only from space, and the precise record extends back only to 1978: the generally accepted mean value of the TSI is about 1361 Wm^{-2} (Kopp and Lean, 2011). Changes in the outgoing LWR can result from changes in the temperature of the earth's surface or atmosphere or changes in the emissivity (measure of emission efficiency) of LWR from either the atmosphere or the earth's surface. For the atmosphere, these changes in emissivity are due predominantly to changes in cloud cover and cloud properties, in GHGs and in aerosol concentrations. The radiative energy budget of the earth is almost in balance, but ocean heat content and satellite measurements indicate a small positive imbalance (Murphy *et al.,* 2009; Trenberth *et al.,* 2009; Hansen *et al.,* 2011) that is consistent with the rapid changes in the atmospheric composition.

In addition, some aerosols increase atmospheric reflectivity, whereas others (e.g., particulate black carbon) are strong absorbers also modifying SWR.

Humans enhance the greenhouse effect directly by emitting GHGs such as CO_2, CH_4, N_2O and chlorofluorocarbons (CFCs). In addition, pollutants such as carbon monoxide, volatile organic compounds, nitrogen oxides and sulphur dioxide, which by themselves are negligible GHGs, have an indirect effect on the greenhouse effect by altering, through atmospheric chemical reactions, the abundance of important gases to the amount of outgoing LWR such as CH_4 and ozone, and/or by acting as precursors of secondary aerosols.

With particular reference to the effects on climate change associated with nitrogen-containing gas emissions, the increasing N_2O production plays an important role in the global warming issue, since N_2O is a powerful greenhouse gas. Nitrous oxide has emerged as such a major GHG issue from agriculture and there has been some debate about the validity of the emission factors used within IPCC (see e.g. Crutzen *et al*., 2016).

Data related to the changes observed in atmospheric greenhouse gas concentrations are represented in the chart of the Figure 1.8.

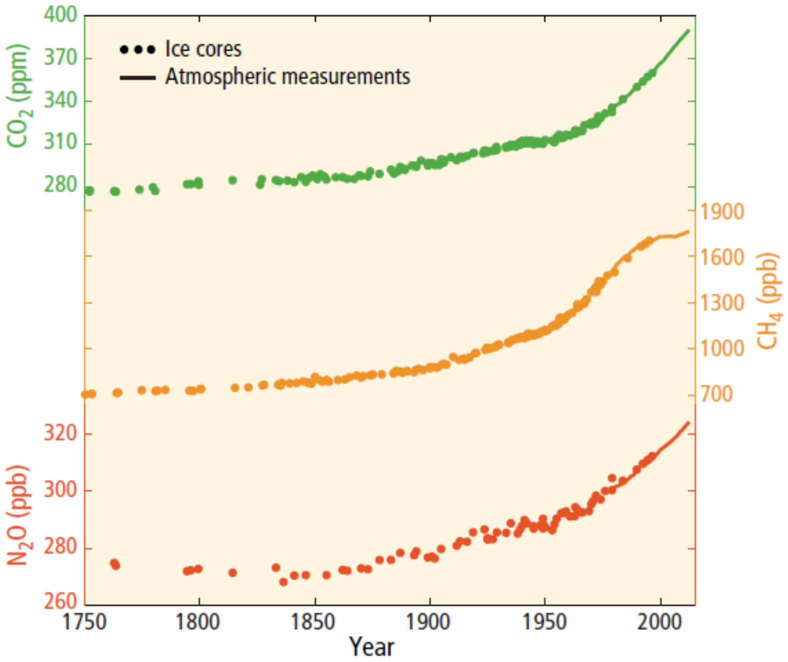


Figure 1.8. *Observed changes in atmospheric greenhouse gas concentrations. Atmospheric concentrations of carbon dioxide (green), methane (orange), and nitrous oxide (red). Data from ice cores (symbols) and direct atmospheric measurements (lines) are overlaid. Source: IPCC Synthesis report (Pachauri et al, 2014).*

Apart from N_2O, there are indications that other chemical forms of nitrogen are emitted that could have a major impact on the global warming potential. Nitrogen trifluoride (NF_3) is about 17.000 times more potent than carbon dioxide.

Weiss *et al.* (2008) demonstrated an increase in the atmospheric concentrations of NF_3 from 0.02 ppt in 1978 to 0.454 ppt in 2008. Their latest measurements reveal a rate of increase of 0.053 ppt yr^{-1} or about 11% per year, corresponding to about 620 t of global NF_3 emissions annually.

Other impacts of nitrogen on the GHG emissions and the net GWP include the effect on carbon sequestration in waters, soils and plants, the effect on aerosol formation causing a direct and indirect cooling effect (through clouds) on the radiation balance and the effect on the emissions of other GHG, such as methane. De Vries *et al.* (2008) for example estimated that the effect of nitrogen deposition on the net GHG emissions for European forests yielded a net reduction in GWP through the additional sequestration of CO_2. Recent debate has focused on the response of forests to this effect. The reported amounts of carbon stored per kg of nitrogen added show a large range from 40 to 400 kg C per kg N deposition (Högberg, 2007; Magnani *et al.*, 2007; De Vries *et al.*, 2008; Reay *et al.*, 2008).

Climate change is one example where the multifaceted interactions of nitrogen cycle with other cycles and elements are understood, as the roles of N_2O and tropospheric O_3 (enhanced due to increased

NO_x emissions) are well understood as a contributing factor in greenhouse gas emissions. However, for other issues, there is a poor understanding of the role of the nitrogen cycle, including its place in the process of carbon sequestration and the interactions among the nitrogen, carbon and phosphorus cycles (Gruber and Galloway, 2008).

1.4.2.2 Eutrophication of terrestrial ecosystems

Eutrophication caused by airborne nitrogen pollution is currently considered the most important impact of air pollution on ecosystems and biodiversity. Excessive atmospheric deposition of nitrogen to ecosystems results in loss of sensitive species, increased growth of species that benefit from high nutrient levels, changes to habitat structure and function, the homogenization of vegetation types (EEA, 2016).

The deposition of N_r is far above levels that the ecosystems are able to absorb and handle without adverse consequences for its vitality. Many ecosystems have changed from nitrogen limited systems to nitrogen saturated systems where nitrogen is not limiting any longer. Long-term high nitrogen deposition loads to ecosystems will also lead to nitrogen leaching into groundwater and surface water runoffs (Sutton *et al*., 2011).

The EU Thematic Strategy on Air Pollution includes an objective for 2020, relative to 2000, of a 43% reduction in areas or ecosystems exposed to eutrophication, areas where eutrophication critical loads are exceeded: the reference measure for this objective is the area in exceedance in 2000. This is in line with the long-term objective of not exceeding critical loads (EEA, 2016).

In 2000, the area of ecosystems where the critical load was exceeded was about 78% of the total in the EU Member States (approximately 60 % in all 33 EEA member countries for which data were available, including the 28 EU Member States) and decreased in 2010 to 63 % in the EU (55 % in all 33 EEA member countries). Assuming that current legislation is fully implemented, the area in exceedance is projected to be 54 % in the EU (48 % in all 33 EEA member countries) in 2020. The reduction is approximately 31 % for the EU, as well as for all the 33 EEA member countries, between 2000 and 2020, which is below the 43 % reduction milestone suggested by the air pollution thematic strategy for this period. Nevertheless, the magnitude of the exceedance is projected to reduce considerably in most areas, except for a few ‘hot spot’ areas, particularly in Belgium, Germany and the Netherlands, as well as in northern Italy. The risk of eutrophication increases slightly when only Natura 2000 protected areas are addressed (EEA, 2016).

Analyzing in detail the emissions of specific pollutants in EU, nitrogen oxide emissions decreased by approximately 43 % between 2000 and 2014. This reduction has been primarily due to the introduction of three-way catalytic converters for cars. However, emission reductions from modern vehicles have not been as large as was originally anticipated. Standard diesel vehicles, for example, can emit up to seven times more NO in real‑world conditions than in official tests (Pastorello and Melios, 2016).

NH emissions have not fallen by as much. In 2014, they had fallen by approximately 9 %compared with their value in 2000 for the EU. Agriculture sector dominates emissions of NH_3; amounting to approximately 95 % of total emissions in the EEA-33 region. Emissions primarily arise from the decomposition of urea in animal wastes and uric acid in poultry wastes.

A key driver behind the observed reductions was the implementation of the National Emission Ceilings Directive, which regulates, inter alia, emissions of the eutrophying air pollutants NO_x and NH_3. However, eutrophying emissions not only from the agriculture and road transport sectors but also from shipping and air travel have been and will remain significant contributors to eutrophication caused by air pollution.

Further reductions in eutrophying air pollutant emissions are expected, inter alia, as a result of the 2012 amended Gothenburg Protocol, which sets air pollutant emission ceilings for 202. Nevertheless, the decreases anticipated for 2020 are not expected to contribute sufficiently to reductions in the ecosystem area exposed to excess nitrogen deposition and affected by eutrophication. In 2020, more than 50 % of the ecosystem areas are expected to be at risk of eutrophication in the EU.

The 2020 thematic strategy objective will therefore not be met unless additional measures to mitigate nitrogen emissions are introduced, through further specific and targeted measures, particularly in the agriculture and transport sectors. Dietary changes resulting in less meat and dairy farming and the reduced use of petrol and diesel in cars could also contribute to reductions. (EEA, 2016).

1.4.2.3 Eutrophication of marine ecosystems

Pollution of coastal seas occurs by the influx of nitrates and Dissolved Organic Nitrogen (DON) through – often transboundary – rivers and by atmospheric deposition. Spatially explicit, quantitative assessments of nitrogen inputs to coastal waters and marine ecosystems are not developed in most large-scale assessment reports. However, there are published studies of nitrogen inputs for individual estuaries in some regions as well as spatially explicit regional and global river nitrogen export models that provide considerable information (eg. Peierls *et al.*, 1991; Meybeck and Ragu, 1995; Smith *et* *al.*, 2003). These studies has highlighted the large variation among rivers, both in terms of nitrogen flux density (kg N/km watershed/yr) and nitrogen load (kg N/watershed/yr), and made it possible to develop a more refined understanding of patterns of nitrogen export at local, regional and global scales. There is considerable spatial variation at local, regional and global scales in the magnitude of nitrogen loading (amount per watershed) as well as nitrogen yield (amount per unit area of watershed) from watersheds to coastal systems (Figure 1.9), with many hotspots around the world.

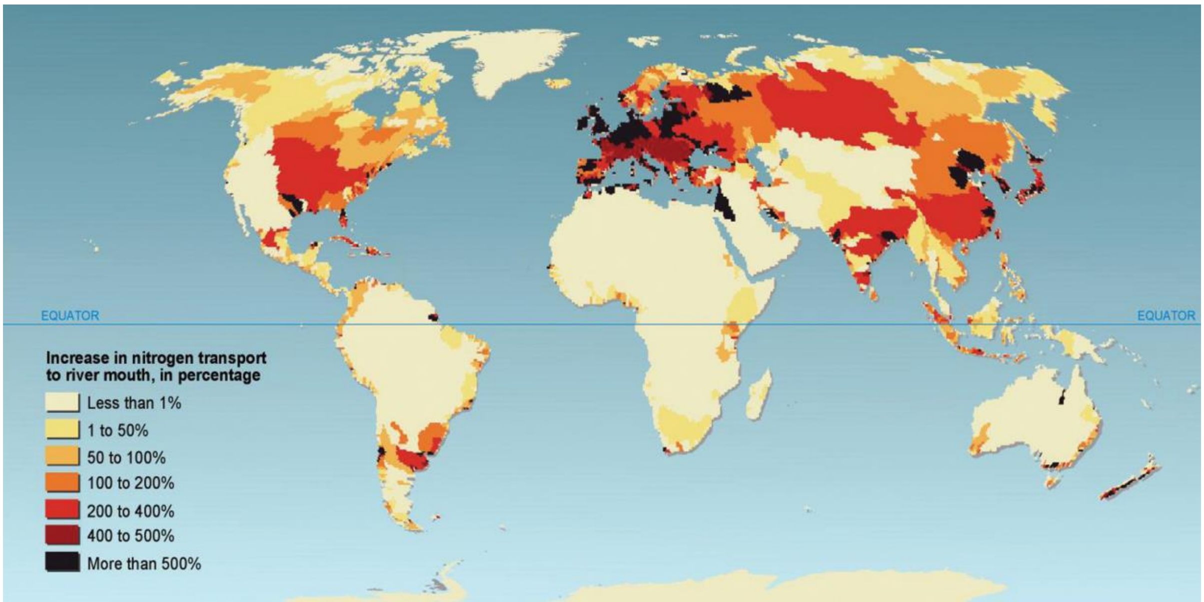


Figure 1.9. *Increase in nitrogen transport to river mouth between 1980 and 2000 (Reid et al., 2005).*

It is clear from the map that Europe forms a hot spot in the world with about the highest increases in nitrogen transport to the river mouth. These hot spots are the result of the growing nitrogen surplus, especially in agriculture. The source contribution varies very much among the different river deltas. In addition, the environmental influence on transboundary outputs is variable.

The amount of nutrients entering the oceans tend to vary significantly over time and from region to region, as do the actions to control the environmental impact. Nutrient enrichment between 1960 and 1980 in the developed regions of Europe, North America, Asia and Oceania resulted in major changes in coastal ecosystems. Estuaries and bays are most affected, but eutrophication is also apparent over large areas of semi-enclosed seas, including the Baltic, North Adriatic and Black Seas in Europe, the Gulf of Mexico and the Seto Inland Sea in Japan (Sutton *et al.*, 2011).

1.4.2.4 Acidification of soils

Acidification of soils, caused by the disturbance of the S and N cycles, is the process of replacement of base cations at the soil's cation exchange complex (CEC) by hydrogen ions.

Although it is mainly attributed to deposition of S compounds, this environmental impact can also be caused by nitrogen compounds: similar to SO_2, input of N in the form of NO_y has a direct acidifying effect, while N inputs as NH_x can be a further source of acidity as a result of nitrification and biological uptake of ammonium (van Breemen *et al.*, 1983).

Inputs of acidifying compounds may lead in the long term to losses of soil buffer capacity by loss of cations, lower pH, increased leaching of nitrate accompanied by base cations, increased concentrations of toxic metals (e.g. aluminium) and changes in the balance between nitrogen species (Reuss and Johnson, 2012).

Acidification makes forests more vulnerable to other stress factors such as frost, drought and pests. A complex multi-causal mechanism is thought to be responsible for the reduced vitality of forests (see e.g., Heij *et al.,* 1991), such as acidification combined with nutrient imbalances and deficiencies caused by N inputs and direct effects of exposure of leaves to air pollutants.

1.4.2.5 Tropospheric ozone formation

The effects on the environment associated with ozone varies depending on the atmospheric section (troposphere or stratosphere) affected by the reactions involving ozone and chemicals that facilitate its formation or destruction.

Unlike some other pollutants of concern such as CO or SO_2, ozone is a secondary pollutant formed in the ambient air through a complex set of sunlight-initiated reactions of its precursors: globally, the majority of tropospheric O_3 comes from photochemical reactions of methane, volatile organic compounds and NO_x, which are largely from anthropogenic emissions. A minor component (approximately 10%) of tropospheric O_3 comes from stratospheric influx. Background O_3 concentration has risen from less than ∼10 ppb before the industrial revolution to daytime summer concentrations exceeding 40 ppb in many parts of the northern hemisphere.

In particular, photodissociation of NO_2 by sunlight is most significant anthropogenic source of O_3 in photochemical smog (Finlayson-Pitts, 1993):

$$\mathrm{NO_2} + h\nu\ \ (\lambda\ < 430\ nm) \rightarrow\ \mathrm{NO} + \mathrm{O} \tag{1.6}$$

$$O + O_2 \overset{M}{\rightarrow} O_3 \quad , \tag{1.7}$$

where:

- *M is any third molecule which is needed to stabilize the excited intermediate formed on the addition of O to O_2.*

Tropospheric ozone is a damaging air pollutant that significantly impacts human and ecosystem health, and is also an important greenhouse gas responsible for direct radiative forcing on the climate. It is estimated to have been responsible for 5%–16% of the global temperature change since preindustrial times and is the second-most important air pollutant (after particulate matter) in causing human mortality and morbidity impacts to human health; globally, an estimated 0.7 million deaths per year are attributed to anthropogenic O_3 pollution

The damaging effects of O_3 on photosynthetic carbon assimilation, stomatal conductance, and plant growth feed forward to reduce crop yields; forests and natural ecosystems are also negatively impacted by current O_3 concentrations, which have downstream consequences for ecosystem goods and service (Ainsworth *et al.,* 2012).

1.4.2.6 Stratospheric ozone depletion

Ozone, like water vapour and carbon dioxide, is an important and naturally occurring greenhouse gas; that is, it absorbs and emits radiation in the thermal infrared, trapping heat to warm the earth’s surface In contrast to the so-called well-mixed greenhouse gases (WMGHGs), stratospheric ozone has two distinguishing properties. First, its relatively short chemical lifetime means that it is not uniformly mixed throughout the atmosphere and therefore its distribution is controlled by both dynamical and chemical processes. In fact, unlike the WMGHGs, ozone is produced entirely within the atmosphere rather than being emitted into it. Second, it is a very strong absorber of short wavelength UV radiation. The ozone layer’s absorption of this UV radiation leads to the characteristic increase of temperature with altitude in the stratosphere and, in consequence, to a strong resistance to vertical motion. As well as ozone’s role in climate, it also has more direct links to humans: its absorption of UV radiation protects much of earth’s biota from this potentially damaging short wavelength radiation. The distribution of ozone in the atmosphere is maintained by a balance between photochemical production and loss, and by transport between regions of net production and net loss.

As for the chemical aspect, stratospheric ozone is produced naturally by photolysis of molecular oxygen at ultraviolet wavelengths below 242 nm:

$$\mathrm{O_2} + h\nu\ (\lambda < 242\ nm) \rightarrow \mathrm{O} + \mathrm{O}\ . \tag{1.8}$$

The atomic oxygen produced in this reaction reacts rapidly with O_2 to form ozone:

$$\mathrm{O} + \mathrm{O_2} \overset{M}{\rightarrow} \mathrm{O_3}\ , \tag{1.9}$$

where *M denotes a collision partner, not affected by the reaction.*

O_3 itself is rapidly photolyzed:

$$\mathrm{O_3} + h\nu \rightarrow \mathrm{O} + \mathrm{O_2}\ . \tag{1.10}$$

O_3 and O establish a rapid photochemical equilibrium through reactions (1.9) and (1.0), and together are called ‘odd oxygen’. Finally, in this sequence of reactions (known as the Chapman reactions), ozone is removed by:

$$\mathrm{O} + \mathrm{O_3} \rightarrow 2\mathrm{O_2}\ . \tag{1.11}$$

A number of different chemical regimes can be identified for ozone. In the upper stratosphere, the ozone distribution arises from a balance between production following photolysis of molecular oxygen and destruction via a number of catalytic cycles involving hydrogen, nitrogen and halogen radical species.

The halogens arise mainly from anthropogenic ozone-depleting substances (ODSs – CFCs, HCFCs and halons). In the upper stratosphere, the rates of ozone destruction depend on temperature and on the concentrations of the radical species. In the lower stratosphere, reactions on aerosols become important. The distribution of the radicals (and the partitioning of the nitrogen, hydrogen and halogen species between radicals and ‘reservoirs’ that do not destroy ozone) can be affected by heterogeneous and multiphase chemistry acting on condensed matter (liquid and solid particles). At the low temperature of the wintertime polar lower stratosphere, this is the chemistry that leads to the ozone hole (de Jager *et al.,* 2005).

With regard, in particular, to nitrogen compounds, the primary source of stratospheric NO_x is surface N_2O emissions. Nitrous oxide shares many similarities with the CFCs, historically the dominant ODSs. The CFCs and N_2O are very stable in the troposphere, where they are emitted, and are transported to the stratosphere where they release active chemicals that destroy stratospheric ozone through chlorine or nitrogen oxide catalyzed processes.

Unlike CFCs, N_2O also has natural sources, akin to methyl bromide, which is another important ODS. In spite of these similarities between N_2O and previously recognized ODSs and in spite of the recognition of the impact of N_2O on stratospheric ozone, N_2O has not been considered, from a legislative point of view, to be an ODS in the same sense as chlorine- and bromine-containing source gases.

1.4.2.7 Particulate matter formation

Airborne particulate matter represents a complex mixture of organic and inorganic substances.

Mass and composition in urban environments tend to be divided into two principal groups: coarse particles and fine particles. The barrier between these two fractions of particles usually lies between 1 μm and 2.5 μm. However, the limit between coarse and fine particles is sometimes fixed by convention at 2.5 μm in aerodynamic diameter ($PM_{2.5}$) for measurement purposes. The smaller particles contain the secondarily formed aerosols (gas-to-particle conversion), combustion particles and recondensed organic and metal vapours. The larger particles usually contain earth crust materials and fugitive dust from roads and industries. The fine fraction contains most of the acidity (hydrogen ion) and mutagenic activity of particulate matter, although in fog some coarse acid droplets are also present. Whereas most of the mass is usually in the fine mode (particles between 100 nm and 2.5 μm), the largest number of particles is found in the very small sizes, less than 100 nm (World Health Organization, 2003).

As for the composition, the main constituents of both PM_{10} and $PM_{2.5}$ all over Europe are generally organic matter, $SO_4^{2-}$and NO_3^-. Mineral dust and sea salt are the main constituents of PM coarse (Putaud *et al.,* 2010).

With regard to the impacts attributable to the particulate matter, the researches show that fine particles (commonly measured as $PM_{2.5}$) are strongly associated with mortality and other endpoints such as hospitalization for cardio-pulmonary disease; a smaller body of evidence suggests that coarse mass also has some effects on health. Few epidemiological studies have furthermore addressed interactions of PM with other pollutants: toxicological and controlled human exposure studies have shown additive and in some cases, more than additive effects, especially for combinations of PM and ozone, and of PM (especially diesel particles) and allergens. Finally, studies of atmospheric chemistry demonstrate that PM interacts with gases to alter its composition and hence its toxicity (World Health Organization, 2003).

Combustion of fuels is a large primary anthropogenic source of particulate matter; sources of secondary PM precursors (gases leading to particulate matter through atmospheric reactions) include gaseous vegetative emissions, motor vehicle emissions, and wood-smoke emissions. Reduced sulfur and nitrogen compounds are oxidized to the particulate components sulfate and nitrate, respectively.

1.4.2.8 Effects of nitrogen on human health

Excess nitrogen inputs to land, air and water can influence human health and welfare in both direct and indirect ways. Some such connections are well known. For example, exposure to high levels of NO_x in urban areas or along roads cause human health problems; the effects of nitrogen-driven increases in tropospheric O_3 and in particulate matter were also presented in the previous paragraphs. Excess nitrate in drinking water may also pose risks for some types of cancer and reproductive problems, though epidemiological data on these links remains too sparse to draw firm conclusions and there is considerable debate and a lack of consensus on the interpretation of medical evidence (van Grinsven *et al.*, 2006; Ward, 2005). In this regard, it is also necessary to emphasize that nitrate intake through drinking water is only part of the total dietary intake, with the main dietary intake of nitrate for many people being from vegetables and meats.

Likewise, uncertainties do not allow an estimate of the health losses related to methemoglobinemia due to drinking water nitrate. Evidence is emerging for possible benefits of nitrate/nitrite as a potential pharmacological tool for cardiovascular health (Wink and Paolocci, 2008).

Although it is not yet possible to estimate net health loss due to nitrate, it is possible to make estimates of potential exposure. Based on data reported to the European Commission about the implementation of the Drinking Water Directive and data on the present nitrate levels in groundwater at drinking water extraction depths, the population in ten west European countries potentially exposed to drinking water exceeding the 50 mg/l nitrate standard, or the 3 mg/l nitrite standard, was estimated at over 9 million (2.7%).

Other feedbacks remain poorly known but are potentially important and costly, including the possible effects of excess nutrients on human infectious and parasitic diseases (Townsend *et al.*, 2003). Diseases that show signs of change following N (and/or P) caused eutrophication include malaria, west Nile virus, cholera and schistosomiasis. These effects are more relevant for other parts in the world. In Europe and in parts of Asia and the USA the exposure of humans to NO_x and PM and the intake of NO_3 is certainly the main threat. Nonetheless, the facts that tropical regions will experience marked increases in nutrient loading and also contain the greatest diversity of human parasitic and infectious diseases highlights the need to understand these connections (McKenzie and Townsend, 2007).

Finally, according to Sanchez and Swaminathan (2005), it is important to note that a healthy immune system requires adequate nutrition, thus one of the most critical links between fixed nitrogen and many tropical diseases may be via its greater supply in fertilizer to undernourished regions (Sutton *et al.*, 2011).

1.5 Nitrogen in the European legislative framework

To conclude the introductory discussion on nitrogen, in this section are reported the main legislative references, at European level, for the management of environmental aspects and the reduction of impacts related to nitrogen emissions in the various environmental compartments.

1.5.1 Industrial emissions

In relation to industrial emissions, the European Union recently issued the ***Directive 2010/75/EU*** of the European Parliament and the Council on industrial emissions (***the Industrial Emissions Directive or IED***). This represents the main EU instrument regulating pollutant emissions from industrial installations. The IED is based on a Commission proposal recasting 7 previously existing directives (including in particular the IPPC Directive) following an extensive review of the policy. The IED entered into force on 6 January 2011 and had to be transposed by Member States by 7 January 2013. The IED aims to achieve a high level of protection of human health and the environment taken as a whole by reducing harmful industrial emissions across the EU, in particular through better application of Best Available Techniques (BAT). Around 50.000 installations undertaking the industrial activities listed in Annex I of the IED are required to operate in accordance with a permit (granted by the authorities in the Member States). This permit should contain conditions set in accordance with the principles and provisions of the IED.

The IED is based on several pillars, in particular:

- an integrated approach,
- use of best available techniques,
- flexibility,
- inspections,
- public participation.

Within this directive is also set up and managed the European Pollutant Release and Transfer Register (E-PRTR): by this instrument, emission data reported by Member States are made accessible in a public register intended to provide environmental information on major industrial activities All relevant emissions from industrial plants, including emissions of nitrogen compounds, are managed and limited within the general framework defined by the IED Directive and by the transposition legislative instruments adopted by Member States.

More information and details are available at the specific official web-site: http://ec.europa.eu/environment/industry/stationary/ied/legislation.htm.

1.5.2 Air emissions from transport

The air pollutant emissions from transport are a significant contribution to the overall state of air quality in Europe: emission of nitrogen compounds are very relevant from this point of view, in relation to the environmental impacts presented in the previous section. Specifically, emissions of particulate matter (PM), nitrogen oxides (NO and NO_2), un-burnt hydrocarbons (HC) and carbon monoxide (CO) are pollutants regulated by "Euro emissions standards".

In general, emission regulations are adopted as part of the EU framework for the type approval of cars, vans trucks, buses and coaches. Current standards are Euro 6 for light duty vehicles (cars and vans), while the current standard for heavy duty vehicles is Euro VI.

It is presented below the current legislative framework for air pollutant emissions from transport:

- ***Directive 2007/46/EC*** provides a common legal framework for the type approval of cars, vans, trucks, buses and coaches.
- Euro 5 and 6 ***Regulation 715/2007/EC*** sets the emission limits for cars for regulated pollutants, in particular nitrogen oxides of 80mg/km.

- ***Regulation 692/2008/EC*** implements and amends Regulation (EC) No 715/2007 on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information
- ***Regulation (EU) 2016/427*** amends Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6)
- ***Regulation 595/2009/EC*** requires new heavy duty vehicles and engines to comply with new emission limits and introduces additional requirements on access to information.
- ***Regulation (EU) 582/2011*** implements and amends Regulation (EC) No 595/2009 with respect to emissions from heavy duty vehicles (Euro VI).

Specifically for various pollutants, successive emission standards have led to significant drops in emissions of exhaust PM and other pollutants such as HC and CO. It must be stated that vehicle emission standards only cover exhaust PM emissions and PM originating from vehicles tire and break wear are currently not part of vehicle regulations. On the other hand, the transport sector is the largest contributor to NO_x emissions, accounting for 46% of total emissions in 2013 in the European Union. However, NO_x emissions, and in particular NO_2 emissions, from road transport have not been reduced as much as expected with the introduction of the vehicle emissions standards since 1991 (especially if compared with other emissions, see Figure 1.10), because emissions in real-life driving conditions are often higher than those measured during the approval tests (in particular for diesel vehicles). It should be noted that urban hotspots of high NO_2 concentrations are even more impacted by vehicle emissions, with transport share rising to more than 60%.

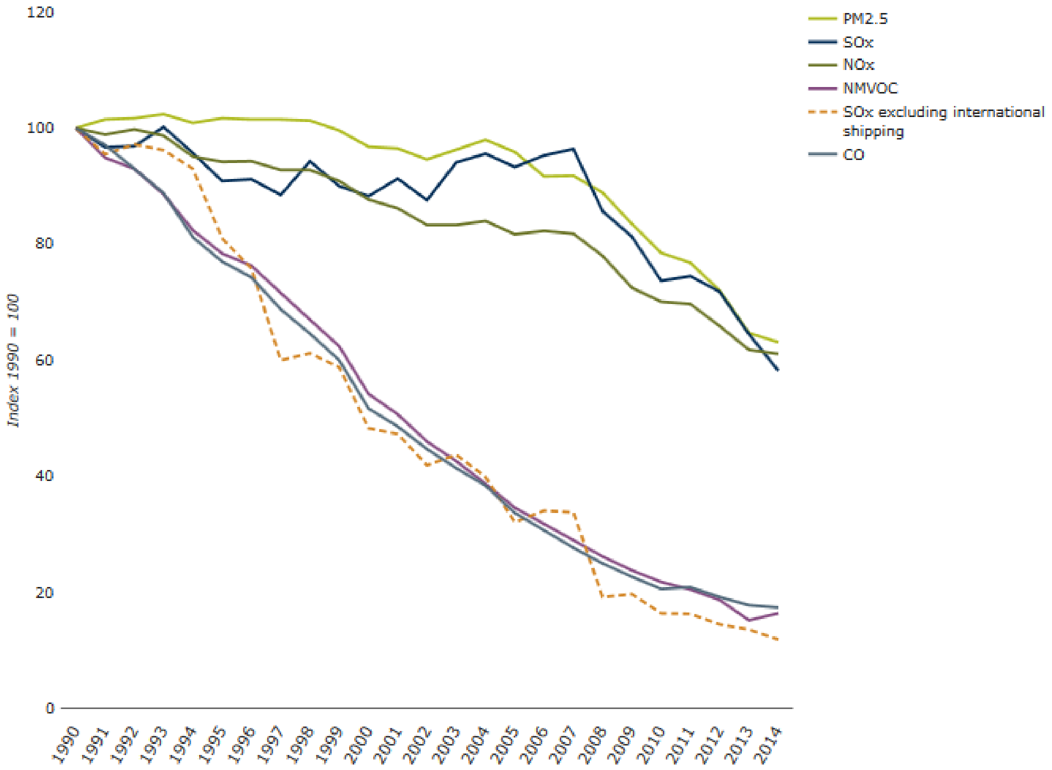


Figure 1.10. *Trend in emissions of air pollutants from transport. Emissions are expressed as the percentage over 1990 levels. Source: European Environment Agency (EEA): national emissions reported to the Convention on Long-range Transboundary Air Pollution (2016).*

To deal with high on-road emissions from passenger vehicles, where a significant discrepancy with the laboratory testing has been confirmed in recent years, the European Commission is introducing the Real Driving Emissions test procedure (RDE) starting from 1 September 2017, which will better reflect the actual emissions on the road and reduce the current discrepancy between emissions measured in real driving to those measured in a laboratory.

The RDE procedure complements the current laboratory based procedure to check that the vehicle emission levels of nitrogen oxides (NO_x), and in a next stage also particle numbers (PN), measured during the laboratory test, are confirmed in real driving conditions.

More information and details are available at the specific official web-site:

http://ec.europa.eu/environment/air/sources/road.htm.

1.5.3 Greenhouse gases emissions

The reduction of greenhouse gas emissions, in the context of the emissions trading system (EU ETS), is one of the key points of EU's policy to combat climate change and is addressed by the ***Directive 2003/87/EC.***

The EU ETS works on the 'cap and trade' principle. A cap is set on the total amount of certain greenhouse gases that can be emitted by installations covered by the system. The cap is reduced over time so that total emissions fall. Within the cap, companies receive or buy emission allowances, which they can trade with one another as needed.

N_2O, as seen above, is one of the main greenhouse gases: the control of the N_2O emissions is therefore included in the European Climate Change Policy.

The system covers the following sectors and gases with the focus on emissions that can be measured, reported and verified with a high level of accuracy:

- carbon dioxide (CO_2) from:
  - power and heat generation;
  - energy-intensive industry sectors including oil refineries, steel works and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals;
  - commercial aviation;
- nitrous oxide (N_2O) from production of nitric, adipic and glyoxylic acids and glyoxal;
- perfluorocarbons (PFCs) from aluminium production.

Participation in the EU ETS is mandatory for companies in these sectors, but:

- in some sectors only plants above a certain size are included
- certain small installations can be excluded if governments put in place fiscal or other measures that will cut their emissions by an equivalent amount
- in the aviation sector, until 2016 the EU ETS applies only to flights between airports located in the European Economic Area (EEA).

With regard to the results obtained, in 2020, emissions from sectors covered by the system will be 21% lower than in 2005; in 2030, under the Commission's proposal presented in July 2015, a reduction of 43% is expected.

More information and details are available at the specific official web-site:
https://ec.europa.eu/clima/policies/ets_en.

1.5.4 Air quality

Air pollution has been one of Europe's main political concerns since the late 1970s. European Union policy on air quality aims to develop and implement appropriate instruments to improve air quality. The control of emissions from mobile sources, improving fuel quality and promoting and integrating environmental protection requirements into the transport and energy sector are part of these aims.

The legislative framework concerning air quality, limited to legislation affecting the nitrogen and its compounds, is composed by:

- ***Council Directive 96/62/EC*** on ambient air quality assessment and management, commonly referred to as the Air Quality Framework Directive. It describes the basic principles as to how air quality should be assessed and managed in the Member States. It lists the pollutants for which air quality standards and objectives will be developed and specified in legislation.
- ***Council Directive 1999/30/EC*** relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air (the so-called "First Daughter Directive"). The directive describes the numerical limits and thresholds required to assess and manage air quality for the pollutants mentioned. It addresses both PM_{10} and $PM_{2.5}$ but only establishes monitoring requirements for fine particles.
- ***Directive 2008/50/EC*** on ambient air quality and cleaner air for Europe that includes the following key elements:
    - The merging of most of existing legislation into a single directive with no change to existing air quality objectives;
    - New air quality objectives for $PM_{2.5}$ (fine particles) including the limit value and exposure related objectives – exposure concentration obligation and exposure reduction target.
    - The possibility to discount natural sources of pollution when assessing compliance against limit values.
    - The possibility for time extensions of three years (PM_{10}) or up to five years (NO_2, benzene) for complying with limit values, based on conditions and the assessment by the European Commission.
- ***Council Decision 97/101/EC*** establishing a reciprocal exchange of information and data from networks and individual stations measuring ambient air pollution within the Member States. This Decision describes the procedures for the dissemination of air quality monitoring information by the Member States to the Commission and to the public.

More information and details are available at the specific official web-site:

http://ec.europa.eu/environment/air/quality/existing_leg.htm.

1.5.5 Water protection

The EU Water Framework Directive (WFD), ***Directive 2000/60/EC***, establishes a legal framework to protect and restore clean water across Europe and ensure its long-term, sustainable use.

The directive establishes an innovative approach for water management based on river basins, the natural geographical and hydrological units and sets specific deadlines for Member States to protect aquatic ecosystems. The directive addresses inland surface waters, transitional waters, coastal waters and groundwater. It establishes several innovative principles for water management, including public participation in planning and the integration of economic approaches, including the recovery of the cost of water services.

The framework directive approach for water has the objective to rationalize the Community's water legislation by replacing seven previous directives: those on surface water and is two related directives on measurement methods and sampling frequencies and exchanges of information on fresh water quality; the fish water, shellfish water, and groundwater directives; and the directive on dangerous substances discharges

More information and details are available at the specific official web-site:

http://ec.europa.eu/environment/water/water-framework/index_en.html.

To the WFD are therefore linked several directives that govern specific aspects, as the Urban Waste Water Treatment Directive (***Council Directive 91/271/EEC***), the Drinking Water Directive (***Council Directive 98/83/EC***), the Groundwater Directive (***Directive 2006/118/EC***), the Bathing Water Directive (***Directive 2006/7/EC***) and the Directive on the assessment and management of flood risks (***Directive 2007/60/EC***).

Nitrogen compounds are certainly among the main potentially polluting substances in water management, so that, for a precise environmental compartment, a specific directive was issued at the beginning of the 1990's and is included in the WFD. This is the ***Council Directive 91/676/EEC,*** also known as Nitrates Directive, concerning the protection of waters against pollution caused by nitrates from agricultural sources. The directive aims to protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices.

The implementation of the Directive provides for the following elements:

- Identification of water polluted, or at risk of pollution,
- Designation of the "Nitrate Vulnerable Zones"(NVZs)
- Establishment of Codes of Good Agricultural Practice to be implemented by farmers on a voluntary basis.
- Establishment of action programmes to be implemented by farmers within NVZs on a compulsory basis.
- National monitoring and reporting

More information and details are available at the specific official web-site:

http://ec.europa.eu/environment/water/water-nitrates/index_en.html.

Parallel to the WFD, whose frame of reference are the river basins, was developed the Marine Strategy Framework Directive (***Directive 2008/56/EC***) establishing a framework for community action in the field of marine environmental policy. The Marine Directive aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend. It is the first EU legislative instrument related to the protection of marine biodiversity, as it contains the explicit regulatory objective that "biodiversity is maintained by 2020", as the cornerstone for achieving GES.

The Directive enshrines in a legislative framework the ecosystem approach to the management of human activities having an impact on the marine environment, integrating the concepts of environmental protection and sustainable use.

More information and details are available at the specific official web-site:

http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm.

1.5.6 Soil protection

Closely connected to the nitrogen cycle is soil protection, defined as the top layer of the earth’s crust, formed by mineral particles, organic matter, water, air and living organisms. As soil formation is an extremely slow process, soil can be considered essentially as a non-renewable resource. The interface between the earth, the air and the water, soil performs many vital functions: food and other biomass production, storage, filtration and transformation of many substances including water, carbon, and nitrogen.

Soil is, however, increasingly degrading, both in the EU and at global level. Erosion, loss of organic matter, compaction, salinization, landslides, contamination and sealing have negative impacts on human health, natural ecosystems and climate.

At the moment, only a few EU Member States have specific legislation on soil protection. Soil is not subject to a comprehensive and coherent set of rules in the Union. Existing EU policies in areas such as agriculture, water, waste, chemicals, and prevention of industrial pollution do indirectly contribute to the protection of soils. But as these policies have other aims and scope of action, they are not considered sufficient by EU to ensure an adequate level of protection for all soils. For this reason, the European Commission, in May 2014, withdrew the proposal for a Soil Framework Directive, to ensure a sustainable use of soils and protect their function in a comprehensive manner in a context of increasing pressure and degradation.

More information and details are available at the specific official web-site:

http://ec.europa.eu/environment/soil/index_en.htm.

Soil protection has been partially taken into consideration at the national level in Italy as part of the requirements of Legislative Decree n. 152/2006, as subsequently amended and supplemented, for the remediation of contaminated sites, which applies to the remediation and environmental recovery of contaminated sites for the elimination of pollution sources and for the reduction of concentrations of pollutants.

The decree specifically foresees concentration limits as a threshold for contamination of soil, subsoil and groundwater for various polluting substances including various nitrogen compounds.

Chapter 2

Nitrogen footprint: applied accounting schemes

This chapter deals with the theme of the nitrogen footprint as a tool for quantifying environmental impacts resulting from alterations in the nitrogen cycle.

Specifically, in the first part of the chapter, the general concept of footprint and the main scientific and regulatory references are illustrated, while, in the second part, are presented the reference tools formulated and partly applied to date for the calculation of the nitrogen footprint.

2.1 Environmental impacts quantification: the footprint indicators

The effect of human activity on the environment manifests itself as an “environmental impact” defined in the international standards as a “change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization’s environmental aspects”, in their turn defined as “elements of an organization’s activities or products or services that interact or can interact with the environment” (ISO, 2015).

Another interesting definition for environmental impact is that used by Morn *et al.* (2009) who defined environmental impact as “the difference between the future state of the modified environment, as it would be following project execution, and the future state of the environment as it would have evolved without such an action”.

In this section is introduced the issue of footprint indicators as tools for the quantification of environmental impacts, with reference to the existing applications and proposals and to the future developments. The concept of footprint indicator is also framed in the wider and more standardized context of Life Cycle Assessment (LCA) methodology for the assessment of environmental impacts of product systems in the life cycle.

2.1.1 Approaches to the formulation of footprint indicators

The relationship between human activities and the environment, which is manifested through environmental aspects and resulting impacts, can be described and governed by tools that address both the assessment of environmental aspects and impacts and their management: most of these tools refer to international standards adopted by the International Organization for Standardization (ISO).

Although the distinction in some cases is not so clear, to simplify, it can be said that the first typology includes tools that can be attributed to the Life Cycle Assessment methodology and to the ISO 14040 family standards; on the other hand, the second group includes tools for the environmental management and the related series standards, whose main reference is ISO 14001.

The present work is geared in particular to deepening methodologies and tools linked, as a first instance, to the impact assessment, therefore the primary reference is the LCA methodology defined as the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006a,b).

In parallel with the LCA tools, the need for quantifying and communicating the environmental impacts of products, services and systems through a shared and standardized methodology has developed in the last years: this need was addressed by the introduction of so-called footprint indicators. The concept of "footprint" originates from the idea of ecological footprint, which was formally introduced to the scientific community in the 1990s (Rees, 1992). Since then, many different footprint-style indicators have been proposed: the water footprint (Hoekstra and Hung, 2002), the energy footprint (Zhao *et al.*, 2005), the exergy footprint (Chen and Chen, 2007), the carbon footprint (Wiedmann and Minx, 2008), the biodiversity footprint (Yaap *et al.*, 2010), the chemical footprint (Sala and Goralczyk, 2013), the phosphorus footprint (Wang *et al.*, 2011), the nitrogen footprint (Leach *et al.*, 2012). Nowadays, footprint indicators have become colloquial and ubiquitous for researchers, consultants and policy makers, and the implications for sustainability and human well-being have been investigated from different perspectives with an increasing interest in similarities, differences, and interactions between some selected footprints (Fang *et al.*, 2014).

Footprint indicators are considered as a guide for investigators, businesses, public sector policymaker and even consumers of everyday goods and services in making decisions, which lead to better environmental outcomes. (Ridoutt *et al.*, 2015; Guariento *et al.*, 2016).

For some of the footprint indicators above presented, international standards have already been proposed and adopted, as specified below:

- regarding carbon footprint of products:

  - ISO/TS 14067:2013 (Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification and communication);
- regarding carbon footprint and greenhouse gas emissions of organizations:
  - ISO 14064-1:2006 (Greenhouse gases - Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals);
  - ISO 14064-2:2006 (Greenhouse gases - Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements);
  - ISO 14064-3:2006 (Greenhouse gases - Part 3: Specification with guidance for the validation and verification of greenhouse gas assertions);
  - ISO 14065:2013 (Greenhouse gases - Requirements for greenhouse gas validation and verification bodies for use in accreditation or other forms of recognition);
  - ISO 14066:2011 (Greenhouse gases - Competence requirements for greenhouse gas validation teams and verification teams);
- regarding water footprint:
  - ISO 14046:2014 (Environmental management - Water footprint - Principles, requirements and guidelines).

With reference to the abovementioned standards, the proposed definitions for footprint are as follows:

- Carbon footprint of a product: sum of greenhouse gas emissions and removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change (ISO, 2013).
- Water footprint: metric(s) that quantifies the potential environmental impacts related to water (ISO, 2014).

Footprint indicators and associated calculation and evaluation methods were initially developed in autonomous and fragmented way and disconnected from the LCA methodologies; recent regulatory and research developments are instead oriented to bring the concept of footprint and its methodologies into the LCA framework, which is certainly more standardized and recognized at international scientific level.

This evolution is evident in the above mentioned definition of product carbon footprint, as well as in the content, to date in the draft phase, of the ISO standard related to the communication of footprint information, which should define footprint as “metric(s) used to report life cycle assessment results addressing an area of concern” (ISO, 2016).

It is useful to remember that the fundamental difference between a footprint indicator and a typical output of a LCA application is that a footprint indicator refers to a specific impact category (eg. climate change, water, nitrogen), while the impact assessment profile of a LCA study provides results for various, and possibly exhaustive, impact categories.

This leads to LCA study reports being rich in technical detail and although valuable in this regard, these reports are generally not widely accessible to people outside the field. This is in contrast to footprints, which have a primary orientation toward non-LCA experts and society in general. Moreover, LCA practitioners work with a set of indicators defined by the LCA expert community. However, these LCA impact category indicators (e.g., terrestrial acidification, particulate matter formation, photochemical oxidant formation) are not necessarily the lens through which society views environmental protection (Ridoutt *et al.,* 2015).

Another fundamental concept in this issue is that of “area of concern”, namely an aspect of natural environment, human health ore resources of interest to society. From this point of view, another distinction between LCA impact category indicators and footprints, is that the latter, with their orientation toward reporting to stakeholders and society, address area of concern, compared to area of protection, that is the ultimate safeguard subject as defined within the expert LCA community (typically: human health, ecosystem quality, and natural resources as endpoint indicators).

In discussing the rationale behind the development of each footprint, Galli *et al.* (2012) showed that footprints are developed in response to a specific environmental issue. For example, carbon footprint relates to global warming, water footprint relates to water scarcity, ecological footprint relates to resource availability in terms of land, and energy footprint is related to energy, which can be converted to ecological footprint or carbon footprint. However, these efforts (Fang *et al.,* 2014; Galli *et al.,* 2012) do not go beyond the original rationale behind development of these footprints, and fail to enhance the performance of these metrics (Singh and Bakshi, 2015).

The need to define a shared methodology for the evaluation of environmental performance was also underlined by the EU in the Commission Recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. In this document was highlighted as “the current proliferation of different methods and initiatives to assess and communicate environmental performance is leading to confusion and mistrust in environmental performance information. It also may lead to additional costs for business if they are requested to measure the environmental performance of the product or the organization based on different methods by public authorities, business partners, private initiatives and investors”. Again, the LCA approach is closely linked to the definition of Product Environmental Footprint (PEF) method as a "general method to measure and communicate the potential life cycle environmental impact of a product" (European Commision, 2013).

Another approach that some researchers proposed was to identify some footprint indicators to be considered exhaustive for quantifying the whole impact over sustainability. This is the case of the Footprint Family of indicators introduced primarily by Galli *et al* (2012) and defined as a "set of accounting tool characterized by a consumption-based perspective able to track human pressure on the surrounding environment, where pressure is defined as appropriation of biological natural resources and CO_2 uptake, emission of GHGs, and consumption and pollution of global freshwater resources". In this proposal, three key ecosystem compartments are monitored, namely the biosphere, atmosphere, and hydrosphere through the Ecological, Carbon, and Water Footprint, respectively.

In this context, however, there are also some authors (Fang and Heijungs, 2013) who expressed reservations about the necessity of LCA to support the establishment of footprints, highlighting the risk of overcounting the impacts, especially in the case of the organization environmental footprint (OEF).

It is finally worth mentioning the input-output analysis approach proposed by Singh and Bakshi (2015) for the footprint metrics that considers "input-side" (impact on ecosystems due to resource extraction) and "output-side" (impact on ecosystems due to waste and emissions disposal). Specifically, the input-side metric takes into account the impact that occurs due to flow of resources as input to human systems from nature as separate from the impact due to emissions to nature. Since, the availability of natural resources depends on the ecosystem's ability to provide or replenish resources; the input side metric indicates the stress on ecosystem health due to resource requirement, if the information about ecosystem capacity is available. On the other hand, the output side footprint is the more traditional viewpoint of looking at the impact of emissions or wastes. An output-side footprint is not purely anthropocentric since emissions also impact the health of ecosystems, however it is more narrowly focused and attempts to aggregate flows that misses other impacts on environment such as due to resource extraction. It is clear from the approach toward carbon footprint, which is mainly focused on emissions of greenhouse gas (Singh and Bakshi, 2015).

2.1.2 Towards a shared definition of footprint

As above highlighted, unlike technical efficiency, which can usually be accurately measured and verified, footprint indicators, with their wider view of environmental performance, are usually calculated using models which can differ in scope, complexity and parameter settings. Despite the noble intention of using footprints to evaluate and report environmental performance, the potential inconsistency between different approaches acts as a deterrent to use in many public policymaking and business contexts and can lead to confusing and contradictory messages in the marketplace (Ridoutt *et al.,* 2015).

Several researchers agree that one way to achieve consistency in footprints is to start with the foundation of the international standards describing environmental management from a life cycle perspective, that is, ISO 14040 and 14044. These international standards predate the recent broad-based popular interest in footprints and do not address the subject directly. Nevertheless, they are the global consensus documents underpinning life cycle assessment, which already supports a wide range of complex environmental decision-making in government and industry (Hellweg and Milà i Canals, 2014).

Starting from the LCA approach, some attempts have been also made to identify the attributes that should characterize all footprint indicators: research in this field is still open and the debate is heated, given the complexity of the subject and the possible implications, especially with regard to aspects of communication to the public.

An interesting proposal of the characteristics which should have a footprint indicator is that made by Ridoutt *et al.* (2015) who identified four defining attributes as follows:

- ***Environmental relevance***. When aggregating data, having common units is necessary, but not sufficient: environmental equivalence is needed. To illustrate, it would not be environmentally meaningful to aggregate emissions of different greenhouse gases without first applying factors, such as those published by the Intergovernmental Panel on Climate Change describing the relative global warming potentials. Similarly, to assess the environmental performance of consumptive water use along a supply chain, it is necessary to apply a model which accounts for differences in local water availability.
- ***Accurate terminology.*** A footprint indicator addresses a specific subject of environmental concern and the indicator’s name must reflect the scope and not be misleading. Where necessary, a qualifying term should be added. For example, following ISO 14046, the term water footprint is applied only when both consumptive and degradative (pollution) aspects of water use are assessed. When only consumptive water use is assessed, water scarcity footprint is a suggested alternative.

- ***Directional consistency.*** Footprints need to follow a consistent logic whereby a smaller value is always preferable to a higher value. This facilitates the easy interpretation of footprints, which is important considering their orientation toward society and nontechnical stakeholders.
- ***Transparent documentation.*** Footprint methodologies and public footprint disclosures need to be supported by documentation enabling technical peer review. Study reports should document all methods, data sources, and assumptions transparently and without bias.

From a technical perspective, footprint indicators might be moreover based on life cycle inventory data (provided the environmental relevance criterion is satisfied), an existing LCA impact category indicator result, or the aggregation of results from different LCA impact categories of relevance to the topic of the footprint. Examples of these three types of footprints are phosphorus depletion footprint, carbon footprint, and water footprint, respectively.

A fundamental contribution to this theme is what will be given by the standard ISO 14026 dealing with the communication of footprint information and which is currently in the draft stage, being therefore under discussion.

While the main purpose of the standard is to define the requirements for a proper communication of environmental impacts through footprint indicators, the standard will also indirectly provide guidance on how the indicators underlying the communication should be coherently designed.

The principles on which the working group that is preparing the standard is converging are the following:

- ***Credibility and reliability.*** Footprint communications should convey information relevant and reliable in terms of addressing areas of concern. In order for footprint communications to be successful in improving environmental understanding of environmental impacts, the working group emphasizes the importance of technical credibility, while adaptability, practicality and cost-effectiveness is provided.
- ***Life cycle perspective.*** Footprint communication should be supported by a structured LCA, which takes into consideration all relevant stages of the life cycle of the analyzed system, including raw material acquisition, production, use and the end-of-life stage.
- ***Comparability.*** Footprint communications should be intended to enable comparison, based on the area of concern, between products in the same product category. Starting from a LCA perspective the functional unit should be the common basis for the comparison.
- ***Transparency.*** A footprint communication and any supporting information should enable all interested parties to access information on where the footprint communication content originated

and how it was developed and verified. This content could eventually be aggregated to protect confidential business information.

- ***Regionality.*** Footprint communications should take into consideration the local or regional environmental context relevant to the area where the corresponding potential environmental impacts occur, including the production, use and end-of-life stages (ISO, 2016).

The conclusions of Ridoutt *et al.* (2015) and the assumptions of the ISO working group (ISO, 2016), show many points of convergence, and in particular they are perfectly aligned with respect to two essential technical prescriptions for the design of footprints indicators: LCA approach and transparency. It should also be pointed out that the latter characteristic is already present in the requirements of the reference standard for the application of LCA as one of the seven principles: "due to the inherent complexity in LCA, transparency is an important guiding principle in executing LCAs, in order to ensure a proper interpretation of the results" (ISO, 2006a).

In conclusion, it is clear that the LCA approach is crucial to the design of a footprint indicator, especially if it is aimed at communicating environmental performance to the public, and as such rigorous approach is also essential for a shared definition of the technical requirements of the indicator.

2.2 Tools for the calculation of the nitrogen footprint

The human use of nitrogen through agriculture, energy use and resource consumption acts on the growing use of reactive nitrogen in the environment; this growth can be seen from two contrasting points of view identifying its positive or negative impacts. Its beneficial effects result from food production and consumption and industrial application, but, on the other side, most of the reactive nitrogen used during these processes and the entire amount formed during fossil fuel combustion are lost to the environment where it causes harmful consequences on people and ecosystem as described in chapter 1. Current estimates, allows to conclude that, following current trends, the need for N_r creation will increase for all sources. Climate mitigation policy may impact such trends if specifically addressing N_2O (see e.g. Oenema *et al.*, 2013). Likely it will not affect continuing high release of N_r to the environment. This provides a collaborative challenge for all stakeholders, including researchers, consumers and governments to reduce the N_r creation rate. Only dedicated policies towards reducing N_r footprints will allow the release of N_r to be mitigated (Galloway *et al.*, 2014). Several tools of nitrogen footprint were developed to properly study, assess, control and manage the release of nitrogen emissions and also to support policymakers, stakeholders, producers and consumers in the active change of the situation.

A summary of the currently proposed and partially implemented tools for nitrogen footprint calculation is given in the following paragraphs.

2.2.1 First experiences for nitrogen footprint calculating

Several groups have examined N_r flows associated with the use of food and energy by people and regions. For example, the Chesapeake Bay Foundation in the US, in partnership with the University of Virginia, developed a calculator (see web site of Chesapeake Bay Foundation: Your Bay Footprint) that estimates a household's contribution to N_r inputs to the Bay resulting from energy use, sewage production, and lawn fertilizer usage.

A much more specific calculator has been prepared to estimate nitrogen, carbon and phosphorus fluxes in 360 household ecosystems in the Minneapolis-Saint Paul, Minnesota (USA) urban region. In this application Fissore *et al.* (2011) found that N_r fluxes into the households were dominated by human diet, lawn fertilizer applications and surface transportation, which together accounted for ~85% of total household N_r inputs.

In a life cycle analysis, Xue and Landis (2010) examined the N and P eutrophication potential of food consumption patterns. They showed that different food groups exhibit a highly variable nitrogen-intensity. On average, red meat and dairy products require much more nitrogen than cereals carbohydrates. An important point they made is that the ranking of nitrogen footprints of foods is not consistent with their carbon footprints. For example, dairy products and chicken/eggs have high nitrogen footprints but low carbon footprints.

2.2.2 The nitrogen-calculator tool

Within a general project named N-PRINT, Leach *et al.* (2012) proposed the first and most structured accounting tool for the nitrogen footprint, the nitrogen-calculator (N-Calculator), with the aim to help consumers to understand and possibly reduce their nitrogen footprint.

According to the design of the authors, N-PRINT should have been a collection of tools, brought together in a system, with the ultimate goal of describing how reactive nitrogen is lost to the environment and its resulting impacts due to individual (consumer) and collective (producers and society) consumption behavior and the ways in which policy can have an effect on these losses (Figure 2.1).

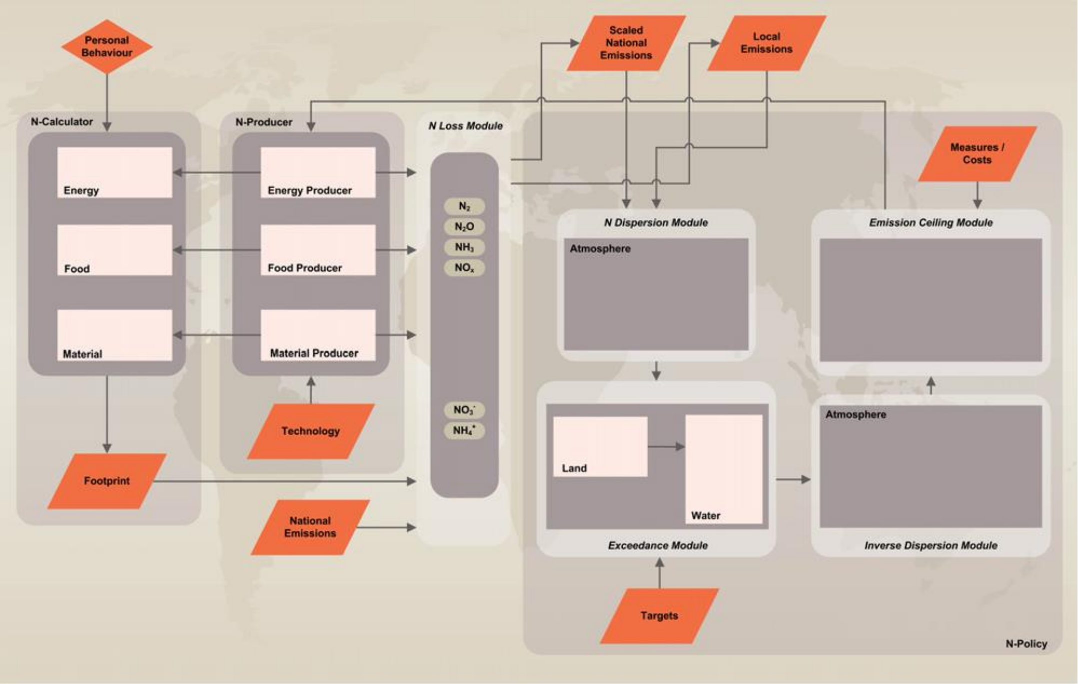


Figure 2.1. *Schematic representation of the project of the N-PRINT system: N-Calculator calculates the consumer footprint; N-Producer calculates the footprint of producers (e.g., farmers) and N-Policy calculates the effect of measures and policies on the nitrogen cycle. Source: Leach et al. (2012).*

Compared to the initial project, currently only the basic tool (N-Calculator) has been implemented, the next steps in the development of the system being to link the reactive nitrogen losses to effects on the environment. The intention of the proposers is to estimate the losses to the environment in terms of emissions to the air (ammonia and NO_x) and the run-off and leaching to groundwater and rivers (nitrate). Subsequently, these results should be linked to the cascading effects in different regions to the global scale, to provide quantitative estimates of the relationship between the virtual nitrogen and the environmental impacts. Finally, data, parameters, and factors should be collected, to enable footprints for different regions/countries in the world.

Within this work was also formulated the most recognized definition of nitrogen footprint as "the total amount of reactive nitrogen (N_r) released to the environment as a result of an entity's resource consumption, expressed in total units of N_r" (Leach *et al.*, 2012).

The N-Calculator web-based tool (www.n-print.org) was designed for individuals in different countries to estimate their contribution to nitrogen losses to the environment focusing on four main areas of consumption: food, housing, transportation, and goods and services. The nitrogen footprint consists of the nitrogen embodied in food consumption and production as well as the NO_x emitted by fossil fuel combustion. The nitrogen footprint of each of the areas of consumption is calculated using average per capita data for a country, allowing for the calculation of a country's average per capita nitrogen footprint as well as the total nitrogen footprint for the country. This average footprint is then scaled appropriately, with an iterative approach, when individuals answer questions – via web – about their personal resource consumption.

In general, within the N-Calculator, the following equation was proposed (with electricity use as an example):

$$FP_{ind} = FP_{avg} \times \frac{EU_{ind}}{EU_{avg}} \quad , \tag{2.1}$$

where:

- *FP_{ind} is the individual footprint (in this case for electricity use),*
- *FP_{avg} the average per-capita footprint for a country,*
- *EU_{ind} the individual electricity use,*
- *EU_{avg} the average per-capita electricity use for a country.*

This equation format can then be used for each component of a nitrogen footprint. The sum of the nitrogen footprints of each component within a sector (e.g. food, housing, transportation, and goods and services) provides the nitrogen footprint by sector, and the sum of the sectors provides the total nitrogen footprint of an individual (Leach *et al.*, 2012).

In particular, the major nitrogen-releasing activities accounted for in the N-Calculator are food (both consumption and production) and energy consumption. The food nitrogen footprint is calculated based on food intake (i.e., FAO estimates of food supply minus food waste) and the amount of nitrogen lost during the production of that food. The food production nitrogen footprint is calculated with virtual nitrogen factors (VNFs), which describe the total nitrogen lost to the environment during production per unit of nitrogen in the final consumed food product. These food production nitrogen losses include fertilizer not incorporated into the plant, crop residues, feed not incorporated into the animal products, processing waste, and household food waste. Recycling within the food production process (e.g., crop residue and manure recycled as fertilizer) is also accounted for in the VNF calculation. The energy component of nitrogen footprint (i.e., the reactive nitrogen released from fossil fuel combustion) in the N-Calculator is accounted using average rates of energy consumption and country-specific emission factors (Shibata *et. al.*, 2017).

As part of its formulation, N-Calculators were completed with data for the United States and the Netherlands. The N-Calculator found that the average per capita N footprint in the United States is 41 kg Nyr^{-1} and in the Netherlands is 25 kg Nyr^{-1} (Figure 2.2).

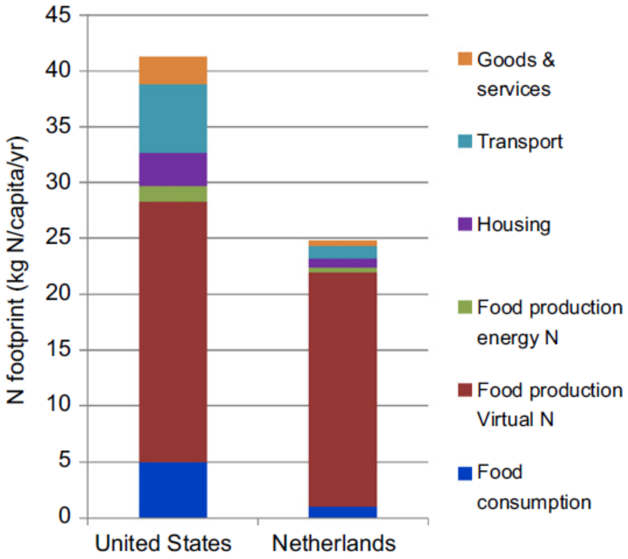


Figure 2.2. *Comparison of United States and Netherlands per capita nitrogen footprints [kg N yr^{-1}capita^{-1}] obtained by applying N-Calculator. Source: Leach et al. (2012).*

Using N-Calculator, per capita nitrogen footprints were been afterwards calculated for Germany (Leach *et al.*, 2012 – updated), UK (Stevens *et al.*, 2014), Austria (Pierer *et al.*, 2014), Japan (Shibata *et al.*, 2014), Portugal (Galloway *et al.*, 2014), Taiwan (Su, 2016), Australia (Liang *et al.*, 2016) and Tanzania (Hutton *et al.*, 2017). The results obtained, as synthesized by Shibata *et al.* (2017) are reported in the Table 2.1.

Table 2.1. *Per capita nitrogen footprints [kg N yr^{-1}capita^{-1}] obtained using the N-Calculator in various countries. Adapted from Shibata et al. (2017).*

Country	**Category** Food	Housing	Transportation	Goods and services	Total
USA	28	3	6	2.5	39
Portugal	24	0.7	3.5	0.5	29
UK	23	2	11	1.1	27
Netherlands	21	0.8	1.1	0.5	23
Germany	19	1.6	1.8	0.7	24
Austria	17	0.8	1.6	0.6	20
Japan	26	0.8	0.7	1.0	28
Tanzania	14	0.2	0.8	0.2	15

Country	Category				
	Food	Housing	Transportation	Goods and services	Total
Taiwan	32	1.7	2	1.7	37
Australia	32	9	2	4	47

Starting from the nitrogen footprint definition of Leach *et al.* (2012) and using a top-down nitrogen balance approach, nitrogen footprints were also calculated for China (Gu *et al.*, 2013), for 12 main food categories within the European Union (Leip *et al.*, 2014a), and with reference to the emissions of four nitrogen compounds for 188 world countries (Oita *et al.*, 2016).

2.2.3 The nitrogen-institution tool

The concept of nitrogen footprint as presented in N-Calculator could be considered as a tool for the connection between entities and the losses of reactive nitrogen due to their activities, and can be considered the reference for all the nitrogen footprints tools subsequently developed.

This concept was extended to institutions in Leach *et al.* (2013), who applied the first institution-level tool to estimate the nitrogen footprint of the University of Virginia, both current (base year 2010) and projected to 2025. The proposed model was one component of the Environmental Footprint Reduction Plan of University of Virginia to quantify and reduce its impacts in four areas of resource use: carbon, nitrogen, waste, and water.

It must be pointed out that a previous calculation example of nitrogen budget for institutions was performed with reference to the Twin Cities campus of the University of Minnesota, addressing the quantification of annual inputs, outputs and internal cycles of nitrogen on the University campus (Savanick *et al.*, 2007).

The nitrogen-institution tool of the University of Virginia was also used to test scenarios on the most effective ways to decrease the nitrogen footprint of the university. The model could be extended to other universities, institutions, and even larger, more complex entities such as cities.

The University of Virginia nitrogen footprint was calculated by tabulating all the reactive nitrogen that entered the institution (e.g., food purchases), that was generated by activities at the institution (e.g., fossil fuel combustion in steam generators and buses), and that was generated due to activities at the institution (e.g., commuting, food production).

The total nitrogen footprint of the university in 2010 was found to be 492 metric tons of nitrogen. As illustrated in Figure 2.3, the most significant contributors were utilities (48%) and food production (37%). The other sectors (food consumption, transportation, fertilizer usage, and research animals) made up the remaining 15 percent. Of the food categories, meat production (23%) and dairy and eggs production (10%) were the biggest contributors (Leach *et al.*, 2013).

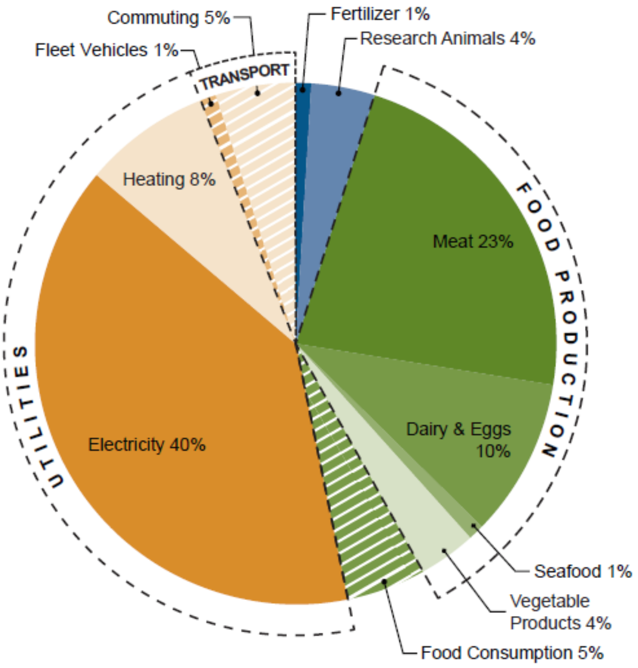


Figure 2.3. *Nitrogen footprint of the University of Virginia in 2010 by sector [percentage on total]. Includes nitrogen released to the environment due to: 1.) food consumption; 2.) food production, reported by specific food categories (vegetable products, seafood, dairy and eggs, meat); 3.) research animals; 4.) transportation, including fleet vehicles and commuter vehicles; 5.) fertilizer application; and 6.) utilities, separated into electricity and heating. Source: Leach et al. (2013).*

If the university were to continue with its current activities (i.e., business as usual) by 2025 the nitrogen footprint would increase by 15% to 564 tons of N due to increased number of buildings and increased student population. However, scenario testing with the tool, showed that, by 2025, the nitrogen footprint could be decreased by 17%, relative to 2025 prevision, with the implementation of planned and feasible activities (e.g., energy conservation, advanced sewage treatment, expanded food composting), and by an additional 14% through further N-reduction strategies (e.g., sustainable food, dietary changes). Institutions can use a nitrogen footprint tool to improve their sustainability by quantifying and reducing their nitrogen impact. Under the authority of the governing board for University of Virginia, the tool is being used to develop strategies to decrease the institution's nitrogen footprint by 25% by the year 2025 (Galloway *et al.*, 2014).

2.2.4 The nitrogen-loss indicator

The nitrogen-loss approach, also used within the Convention on Biological Diversity, assumes that inefficient use of fertilizer and/or fossil fuels results in loss of reactive nitrogen to the environment. Eventually, the lost reactive nitrogen to the environment can end up close to the sources or in remote areas located far from human activities, where it is often the dominant source of reactive nitrogen. Once introduced there, the increased reactive nitrogen levels can severely affect associated biodiversity (see http://www.bipindicators.net/nitrogenloss).

This associated nitrogen loss indicator shows the reactive nitrogen loss for different regions of the world as a result of the production and consumption of food and the use of energy (e.g. for electricity production, industry and transport), and is expressed as the reactive nitrogen loss per capita per year, without making a distinction between losses to air, soil and water (Bleeker *et al.*, 2012).

While the N-Calculator tool accounts for the loss of nitrogen due to consumption by individuals, the nitrogen-loss indicator shows the loss due to production and consumption in a country. This calculated loss is a surrogate measure of potential reactive nitrogen pollution; the actual pollution depends on environmental factors and the extent to which the waste flows at production and consumption of food and energy are being reused (

An example of the application of this tool for different regions in the world is reported by Galloway *et al.* (2014): in this example the results for the different regions are averages for the underlying countries, for which separate calculations were performed (Figure 2.4).

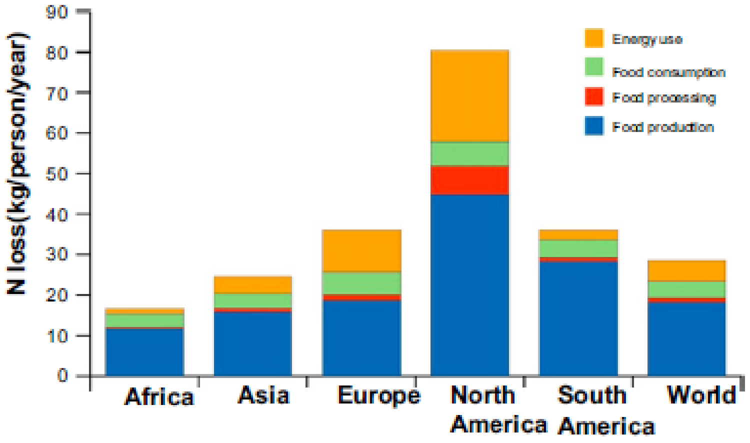


Figure 2.4. *Average loss of reactive nitrogen per inhabitant in 2008 [kg person^{-1} yr^{-1}] as example of the application of the nitrogen loss-indicator. Source: Galloway et al. (2014).*

According to the results presented, in 2008 the global production and consumption of food and energy results in an average reactive nitrogen loss of 28 kg of nitrogen per inhabitant per year. Of the total loss, 5 kg is the result of energy use, 18 kg is from food production (agriculture), 1 kg due to food processing and 4 kg is released during food consumption. The European reactive nitrogen loss per person is about 10 kg higher than the global average loss and is almost half of that in North America, but twice as high as in Africa. The energy component is relatively large in industrialized countries, while the contribution of food production and consumption is large in countries with an extensive livestock sector and high levels of meat consumption.

By applying the approach underlying the nitrogen-loss indicator, a link between dietary choice in Europe and reactive nitrogen flows was also established by Westhoek *et al.*, (2013), who found that a reduction in livestock production would lead to a significant decrease in the reactive nitrogen input and losses. In their hypothesis of greening scenario, under a 50% reduction in all meat and dairy consumption, fertilizer input would be reduced from 11.3 to 8.0 million ton Nyr^{-1}, while emissions of nitrates to groundwater and surface water and ammonia to air both would be reduced by 40%, compared with the reference situation.

2.2.5 The nitrogen-neutrality tool

The nitrogen footprint tools presented above focus on informing the users about their nitrogen footprint and possibly proposing actions that would lead to a reduction of the nitrogen footprint. The concept of nitrogen-neutrality proposed by Leip *et al*. (2014b) describes a way to compensate the nitrogen footprint that could not be reduced by any of the mitigation measures.

In this proposed tool, basing on the carbon-neutrality concept, nitrogen-neutrality was defined as a two-step approach focusing on (1) the measures that avoid and/or reduce the release of N_r, before (2) purchasing nitrogen offsets that compensate the residual N_r releases (Figure 2.5). This can be done either by a measured reduction of N_r releases elsewhere to balance the remaining releases, or by an increase of the sustainability in the production of food where sustainable land management is not yet achieved.

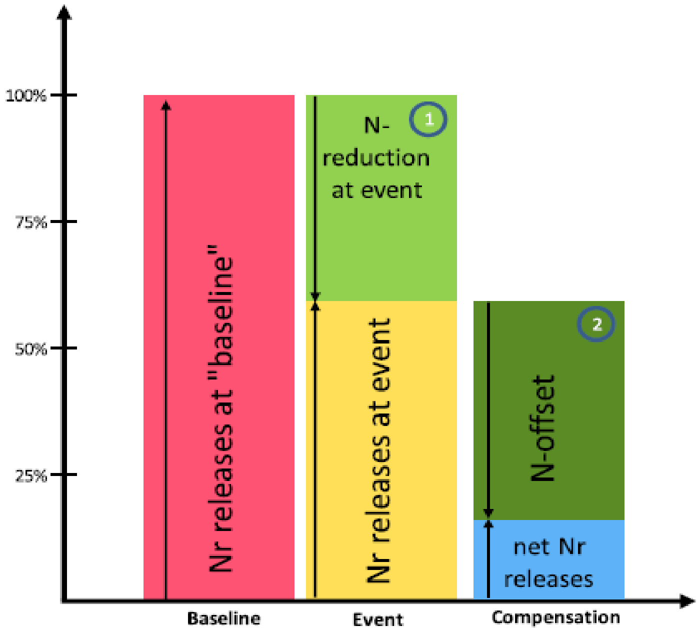


Figure 2.5. *Schematic representation of the nitrogen-neutrality concept. First, the baseline of* N_r *releases is calculated to determine what the* N_r *releases would be if no measures were taken. Second, measures to reduce* N_r *releases from the event 'baseline' are implemented (point 1). Finally, the residual* N_r *releases are compensated with nitrogen offsets according to the definition of nitrogen-neutrality (point 2). Nitrogen-neutrality is achieved if there are no remaining net* N_r *releases of the event. The concept is showed here for the Nitrogen Conference 2013 (achieving 41% reduction in step 1 and a calculated offset of 73% in step 2). Source: Leip et al. (2014b).*

This concept was implemented at the 6th International Nitrogen Conference (Kampala, November 2013). Participants of this conference were asked to contribute with a compensation fee to support the UN Millennium village cluster Ruhiira South–Western Uganda, to increase soil fertility with afforestation programs. The nitrogen offset required to compensate the nitrogen footprint of the conference was quantified on the basis of surveyed total food consumption of the conference attendants. The energy nitrogen footprint was not considered for this first application of nitrogen-neutrality.

In particular, the total nitrogen footprint of the 6th International Nitrogen Conference was calculated, using the N-Calculator model, as 66 kg of nitrogen lost to the environment. Total nitrogen intake by actual food consumption over the five-days conference was surveyed at 12.9 kg N, for an average of 140 persons at each meal served. Contributions to the nitrogen footprint were: dinner 35%, lunch 31%, breakfast 17% and morning and evening tea 8–9% each. Meat (beef, pork, chicken, goat and mutton, fish and seafood) and staple food (matooke, rice, sweet and Irish potatoes, cassava, maize, cereals) contributed equally to the nitrogen footprint with 37% each, followed by fruit and vegetables

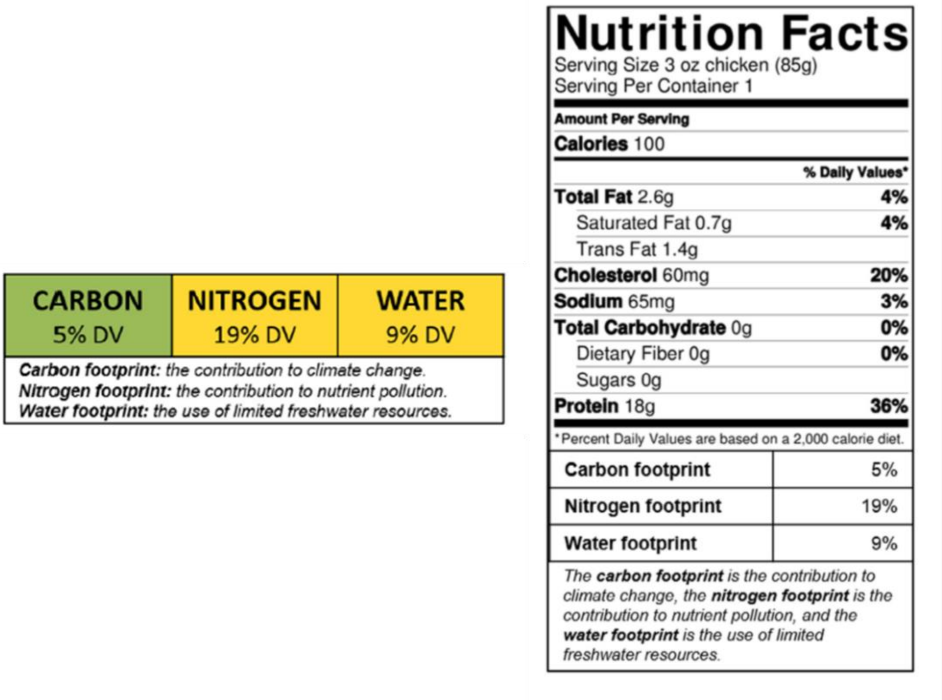
(17%), animal products (milk and eggs, 7%). Leguminous crops (groundnuts, beans and peas) contributed less than one percent, but 3% of fresh weight intake and 8% of protein intake. Luxury food (tea, coffee, sugar) – the one food group which consumption was significantly higher when compared to the baseline conference – contributed 2% to the nitrogen footprint of the conference.

On the basis of a preliminary estimate of the nitrogen footprint (giving a much higher value of about 150 kg N = 705 g N cap^{-1} multiplied for 200 cap), a compensation fee of US$ 50 was estimated and requested from the participants as voluntary maximum contribution to N-neutrality. With 160 registered participants and a resulting per capita nitrogen footprint of 0.41 kg N per registered person (which is lower than the footprint of the for the average nitrogen footprint per person present at the meals of 0.47 kg N, due to shorter attendances or ‘skipped’ meals), the cost per person dropped to US$ 26 per person (note that no energy-related N_r releases were included in the calculation). From the 160 registered delegates, 61 persons donated up to US$ 50, where by the donations were topped-up to US$ 50 by sponsors, giving a total of collected money of US$ 3050 (or about 73% of the total calculated required compensation fee) and invested in the compensation project (Leip *et al*., 2014b).

2.2.6 The nitrogen-label tool

Nitrogen footprints and indicators above presented can give entities an indication of their overall nitrogen sustainability, however these tools do not provide consumers with understandable information about an individual product. For this reason, some researchers (firstly Leach *et al.*, as reported in Galloway *et al.*, 2014) proposed environmental food label presenting the nitrogen footprint of a single food product to show that food product’s contribution to nutrient pollution. The proposed label should be designed to be printed directly on a food product’s packaging to help consumers make decisions at the grocery store. In this hypothesis, the nitrogen footprint food label should be presented as a percent of the daily nitrogen footprint calculated for a sustainable diet and the percent daily value concept based on the units for nutritional recommendations on existing United States Department of Agriculture (USDA) food labels. The percent daily value should describe how much of the daily allotted food nitrogen footprint for a sustainable diet is contained in a single serving of food. For example, if a sustainable diet has nitrogen footprint of 41 g N day^{-1} and a serving of food has a nitrogen footprint of 8 g N, then the percent daily value would be 19% (in this example defining the sustainable diet as a healthy diet recommended by the USDA). Although the healthy diet is not directly linked to environmental impacts and is therefore not a true indicator of sustainability, in this hypothesis it was used because the diet recommendation must meet minimum health requirements for humans and because a healthy diet does approach sustainability with its emphasis on low-impact food, such as non-meat proteins, in comparison to the current average US diet (Galloway *et al.*, 2014). A subsequent and more detailed proposal was made by Leach *et al.* (2016) who suggested a comprehensive environmental impact food label assessing a food product’s sustainability in terms of its energy, nitrogen, and water use by three specific metrics: the carbon, nitrogen, and water footprints, respectively. According to the authors, taken together, these indicators should provide information about how a specific food product impacts the environment during its production.

Two possible examples of application of the proposed label with reference to the chicken are shown in the Figure 2.6: for details on the calculations see Leach *et al.* (2016).



CARBON	NITROGEN	WATER
5% DV	19% DV	9% DV

Carbon footprint: *the contribution to climate change.*
Nitrogen footprint: *the contribution to nutrient pollution.*
Water footprint: *the use of limited freshwater resources.*

Nutrition Facts
Serving Size 3 oz chicken (85g)
Serving Per Container 1

Amount Per Serving	
Calories 100	
	% Daily Values*
Total Fat 2.6g	**4%**
Saturated Fat 0.7g	**4%**
Trans Fat 1.4g	
Cholesterol 60mg	**20%**
Sodium 65mg	**3%**
Total Carbohydrate 0g	**0%**
Dietary Fiber 0g	**0%**
Sugars 0g	
Protein 18g	**36%**

*Percent Daily Values are based on a 2,000 calorie diet.

Carbon footprint	5%
Nitrogen footprint	19%
Water footprint	9%

*The **carbon footprint** is the contribution to climate change, the **nitrogen footprint** is the contribution to nutrient pollution, and the **water footprint** is the use of limited freshwater resources.*

Figure 2.6. *Two proposals of environmental impact food label designs showing the carbon, nitrogen, and water footprints of chicken: stoplight label (on the left) and US FDA nutrition label add-on (on the right). The percentage daily value calculation method was used for all label designs. Source: Leach et al. (2016).*

The authors concluded that, regardless of the label selected, an environmental impact labeling strategy could be more effective if a single, integrated label was used across a broad range of food products and retailers. The incorporation of footprint labels onto food products could both increase public awareness of the environmental impacts associated with food production as well as support producers who provide sustainable products (Leach *et al.*, 2016).

It must be underlined that the risk of misleading or incorrect communication is very high in the case of such instruments. Labeling, aimed at consumer communication, should therefore be supported by an adequate and transparent calculation system and by appropriate verification by third party bodies.

2.2.7 Process-based environmental LCA for nitrogen flows quantification

In the context of the nitrogen footprint accounting tools presented, a very interesting proposal, because closely related to the research that will be presented in the following chapters, is that of Pelletier and Leip (2014), who developed a methodology based on a life-cycle approach. They implemented a two-step method (consisting of classification and characterization) for systematic inventorying and aggregation of nitrogen mobilization, flows in product systems and emissions in life cycle assessment.

Compared to the tools described above, this methodology presents a more evident and LCA approach, applied by the authors in view of the fact that arriving at robust and consistent quantification of the magnitude and distribution of fixed nitrogen mobilization, flows and losses, and effective management strategies, should be facilitated by the application of common life cycle-based tools and approaches.

Given the potentially serious consequences of continued perturbation of the global nitrogen cycle as a result of anthropogenic mobilization and losses of fixed nitrogen, as well as the likelihood that management of nitrogen will be increasingly prominent in policy agendas for both environmental and socioeconomic reasons, the authors suggested that a consistent inventorying and quantification method for nitrogen in LCA research should be desirable (Pelletier and Leip, 2014).

In particular, they applied specific characterization factors to a previously compiled life cycle inventory data set representative of a subset of consumption attributable to the average consumer in the 27 member states of the European Union in key demand categories for the base year 2006. The inventory data set used was that compiled to support development of the European Commission Basket-of-Products Indicator.

With regard to the results obtained, the calculated life cycle fixed nitrogen emissions attributable to average consumption of the modelled products in the key demand categories in 2006, including production, use and end-of-life phases, amounted to 8.3 kg per capita. Of these, almost 100 % were in the form of emissions of ammonia (38%), nitrogen dioxide (33%), nitrate (24%), nitrous oxide (4%) and nitrogen monoxide (1%). Emissions were also assessed based on life cycle stage (production, use, and end-of life) and demand category. On this basis, it was determined that the "nutrition" demand category—specifically, the (food) production phase—accounted for 63% of total emissions (and 90% of production-related emissions overall). The second largest share of emissions (19%) is attributable to the shelter demand category, largely for the use phase. The use phase of the mobility demand category is also significant (11%). Production and end-of-life phases make minor contributions (2% each) across the consumer goods, mobility and shelter demand categories (Figure 2.7).

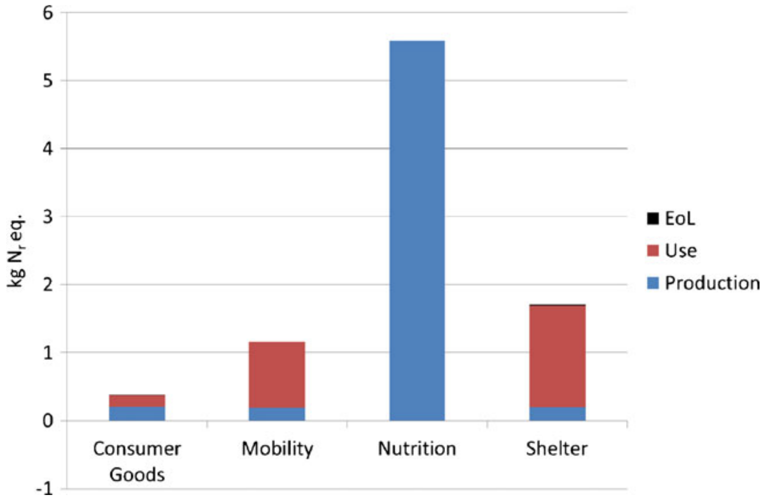


Figure 2.7. *Results of application of a LCA based methodology for nitrogen footprint calculation. Emissions of fixed nitrogen associated with consumption of representative products in key demand categories for the average EU-27consumer in 2006 (by life cycle stage and demand category). Source: Pelletier and Leip (2014).*

The use of an LCA approach in the proposed methodology is also evident from the method chosen for the representation of results highlighting the contribution of each stage of the life cycle for the selected demand categories.

In their work, Pelletier and Leip (2014) also outlined that data set obtained were consistent with those observed from studies having a similar scope but different methodological approach. This outcome suggested that nitrogen could, indeed, be systematically inventoried and aggregated in process-based LCA for the purpose of providing information for decision support.

2.2.8 Nitrogen footprint existing tools: a critical review

A critical analysis of the nitrogen footprint tools described is provided below, in order to highlight the main features of each methodology and to compare with what was illustrated about the features that should ideally have the footprint indicators according to latest research and standard requirements.

A synthesis of the main features of the presented nitrogen footprint tools is reported in the Table 2.2.

Table 2.2. *Comparison of the main characteristics of different applied nitrogen footprint tools.*

Footprint tool	**Proposed by**	**Target**	**Scope**	**Unit of measure**	**LCA approach**	**Assessment level**
Nitrogen calculator	Leach *et al.* (2012)	Individuals	N_r released for food use and energy related items	kg N yr^{-1} $capita^{-1}$	Limited	Inventory
Nitrogen institution	Leach *et al.* (2013)	Institutions	N_r released for food use and energy related items	kg N	Limited	Inventory
Nitrogen loss indicator	Convention on Biological Diversity (2010)	Countries	N_r released for food production / consumption and energy use	kg N yr^{-1} $capita^{-1}$	Limited	Inventory
Nitrogen neutrality	Leip *et al.* (2014b)	Events (Processes)	Nitrogen offsets to compensate N_r releases	kg N converted in monetary u.o.m. (€/$)	Limited	Inventory
Nitrogen label	Leach *et al.* (2016)	Products	Fraction of daily allotted food nitrogen footprint for a sustainable diet	%	Limited	Inventory
Process based LCA approach	Pelletier and Leip (2014)	Processes	Products emissions of fixed nitrogen	kg N_r equiv.	High level	Inventory

The analyzed characteristic “LCA approach” refers to the degree of application of LCA methodology and requirements – as presented within the reference standards (ISO, 2006a,b) – for the design and the calculation of the nitrogen footprint. As can be seen, a limited LCA approach was attributed to all the footprint tools other than the process based LCA prosed by Pelletier and Leip (2014). This is mainly because the primary purposes of the tools were different from a life cycle evaluation: the data set used for the accounting are therefore not designed for application to LCA studies and not related to the whole life cycle. For this same reason, the concepts of product system and reference unit, which are fundamental for the LCA approach, are not present and developed.

Another interesting feature for the analysis is the "assessment level", that is the stage, referred to the phases of LCA studies, with respect to which the indicator provides the environmental information. An inventory level means that the indicator provides information about the incoming and outgoing flows, of nitrogen in this specific case, of the product system being the subject of the analysis. Unlike an impact level indicator, an inventory level indicator does not provide information about the environmental impacts that the incoming and outgoing flows can potentially cause (eg. for the nitrogen in terms of eutrophication, greenhouse effect, acidification, etc.).

As far as the analysis is concerned, it should be noted that two of the listed tools, nitrogen neutrality and nitrogen label, do not have, as their main purpose, the accounting of the nitrogen footprint, as described above. In this case, regarding the degree of application of the LCA approach and the level of accounting, the critical analysis was performed with reference to the underlying calculation tools.

In conclusion, it is evident that, if the LCA approach must be considered a prerequisite for the design and implementation of a footprint indicator, most of the tools developed to date can be improved for this feature. In particular, as underlined also by Pelletier and Leip (2014), consistency and comparability of studies for nitrogen footprint accounting, are hampered by the current lack of common methodologies and, can be added, by the lack of use of databases and calculation tools specifically designed for LCA applications.

In addition, a further effort could be made in order to implement a nitrogen footprint indicator that can also provide information related to the environmental impacts caused (impact level) by the entity or by the product system analyzed and not only to the reactive nitrogen streams (inventory level).

Chapter 3

A new methodology for the assessment of impact related to the nitrogen cycle

This chapter presents the proposed methodology for the calculation of environmental impacts related to the nitrogen cycle. Specifically, in the first part of the chapter, the assumptions and the general framework on which the methodology is designed are described while, in the second part, the methodology is presented describing in detail all the provided phases and steps and the underlying conceptual and mathematical models.

3.1 Towards a nitrogen impact assessment based on a LCA approach

Starting from the considerations concerning the formulation of footprint indicators reported in the chapter 2, and in particular form the weakness points highlighted by most of the currently existing tools for nitrogen footprint calculation, a new proposal of methodology must certainly be consistent with the following requirements:

- life cycle assessment (LCA) framework setting;
- impact assessment approach.

As far as the first requirement is concerned, as noted, the LCA approach should be the basis for implementing any footprint indicator as it is the most widely used and scientifically recognized methodology for the assessment of environmental impacts of an entity or product system. For the proposed methodology, LCA must be used as a framework for the whole approach, form the design to the implementation and application as well as a reference for setting up calculation and impact assessment models.

Regarding the second requirement, it is considered that the new proposal should present an approach designed to identify and quantify also the specific environmental impacts of the analyzed system, with reference to the perturbation of the nitrogen cycle. The reactive nitrogen accounting, used as a common denominator for the definition of nitrogen footprint in the tools so far proposed, is actually defined only at an inventory level, that is, it only takes into account the input and output flows from the system being studied. To date, no attempts were made to implement a nitrogen footprint assessment accounting the environmental impacts arising from the analyzed flows, as is normally the case for the LCA studies, specifically through the impact assessment phase: the proposed methodology must specifically respond to this specific assessment need.

3.1.1 The life cycle assessment framework

Life cycle assessment is a methodology for the identification and assessment of the environmental impacts of a product system over its life cycle. The methodology, as today known and applied, results from further investigation of the first applications of merely energy analysis passing through comprehensive environmental burden analysis in the 1970s and up to full-fledged life cycle impact assessment and life cycle costing models introduced in the 1980s and 1990s. Specifically, the actual definition of LCA comes from a period of convergence through Society of Environmental Toxicology and Chemistry (SETAC)’s coordination and ISO’s standardization activities, providing a standardized framework and terminology, and platform for debate and harmonization of LCA methods (Guinée et al., 2011).

As standardized by ISO (2006a,b), the LCA methodology for the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle requires 4 phases, as follows:

- ***Goal and scope definition:*** is the initial step in which the goal and scope of an LCA shall be clearly defined and shall be consistent with the intended application. Due to the iterative nature of LCA, the scope may have to be refined during the study. In this phase must be addressed issues related to the product system, its functions and functional unit, system boundaries, methodology of impact assessment and selected impact categories, interpretation, data requirements, assumption, limitations, initial data quality requirements, type of critical review, type and format of report.
- ***Inventory analysis:*** is the step which includes data collection and the method that allows the quantification of the entering and leaving flow of a product system, in relation to the defined boundaries of the system. In this phase the knowledge of the system increases and may emerge the need to change assumptions respect to the initial considerations, such as the system boundaries or procedure for data collection, or sometimes may be also necessary to review the scope or

objective. The iterative nature of the process allows the identification of new data requirement, limitations or collection of other data to completely satisfy the goal of the study. In particular, the data collection regards the quantification of entering or leaving elements of a unit process: input of energy, raw material, physical entities as well as products, co-products, waste, emissions to air or discharges to water and soil.

- ***Impact assessment:*** is the step in which the assessment of potential environmental impacts is performed, starting from the results coming from inventory phase: inventory data are associated with specific environmental impact categories and related indicators. According to ISO 14040, an impact categories indicator is defined as quantifiable representation of an impact category. Impact categories represent a class of environmental issues to which life cycle inventory analysis results may be assigned: they describe the potential effects on humans and ecosystems, affecting the environment at local, regional and global. Examples of impact categories are acidification, ozone depletion, human toxicity, global warming, ionizing radiation, photochemical ozone formation, ecotoxicity, eutrophication, resource depletion, land use.
- ***Interpretation:*** this phase consists in the correlation of results obtained from the inventory analysis and environmental impact assessment. The aim is to reach conclusions and provide an easily understandable, complete and consistent presentation of LCA study result in a transparent manner, according with goal and scope of the study, highlighting also the area where improvements could be implemented. It is carried out according to the goal and scope definitions, including system functions, functional unit and system boundaries.

In accordance with or above the requirements, a general supporting framework is proposed for the nitrogen footprint assessment that follows the requirements of the reference standards for LCA. In particular, a section preliminary defined as “nitrogen inventory study” starts from the ***goal and scope definition*** – with characteristics and requirements similar to those of the corresponding phase of the LCA methodology – and incudes the ***nitrogen inventory analysis*** aimed at describing the flows that affect the product system with reference to the substances relevant for nitrogen cycle alterations.

A further section, defined as ***nitrogen footprint assessment***, which starts from the outputs of the previous section, includes the phase of assessment of impacts generated by the product system limiting the scope to the impact categories that have a direct bearing on the nitrogen cycle perturbations.

As a corollary is the ***interpretation*** stage that concerns the findings from the nitrogen inventory analysis and the nitrogen footprint assessment, with the aim to deliver results that are consistent with the defined goal and scope of the application, to reach conclusions, explain limitations and provide recommendations.

A schematic representation of the general framework underlying the proposed methodology is presented in the Figure 3.1: the declination of the general framework in the proposed methodology with a precise identification of the phases and of the steps is presented later in this chapter, starting at § 3.2.

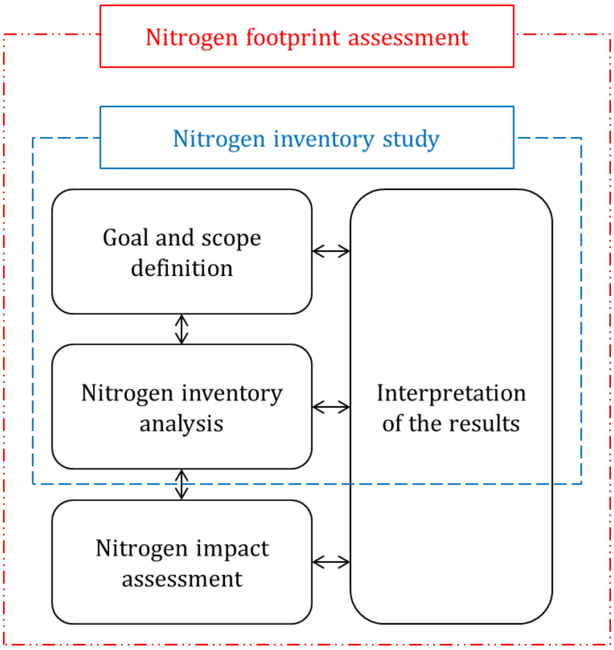


Figure 3.1. *Schematic representation of the framework underlying the proposed methodology for nitrogen footprint assessment, comprising the sections of nitrogen inventory study and nitrogen impact assessment. Adapted from ISO (2006a,b).*

One of the key concepts for the proposed methodology, derived from the requirements for LCA studies, is that of product system, that is the mode used to model the reference entity that is the subject of the study or application. LCA approach models the life cycle of a product as its product system, which performs one or more defined functions. Product systems are usually subdivided into a set of unit processes. Unit processes are linked to one another by flows of intermediate products and/or waste for treatment, to other product systems by product flows, and to the environment by elementary flows. The level of modelling detail that is required to satisfy the goal of the study determines the boundary of a unit process (ISO, 2006a).

Another essential concept to be applied in the proposed methodology, and once again reflecting the LCA approach, is that of function of the product system. A system may have a number of possible functions and the one(s) selected for a study depend(s) on the goal and scope of the assessment. With reference to the system function, the functional unit defines the quantification of the identified functions (performance characteristics) of the product system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of results that is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis (ISO, 2006a).

An example of representation of a product system, including unit processes, elementary and product flows is shown in the Figure 3.2.

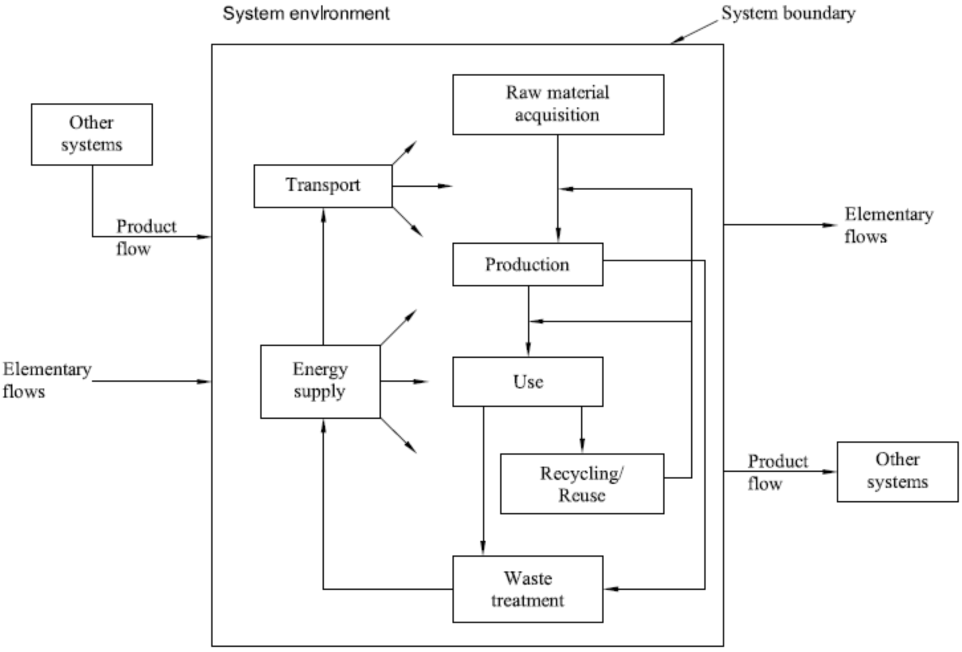


Figure 3.2. *Example of scheme for LCA product system representation. Source: ISO (2006a).*

The choice to systematically adopt an LCA approach for the proposed methodology is in line with what is required by the latest interpretations for the formulation of footprint indicators and then allows the model to be potentially applied to any entity, using furthermore a method derived from international standards recognized by the scientific community.

3.1.2 The impact assessment approach

As above highlighted, the proposed methodology comprises a specific phase aimed to evaluate the environmental impacts arising from the product system with reference to the impact categories that describes the perturbations caused to the nitrogen cycle. This element constitutes a new approach in the nitrogen footprint accounting, being the models currently proposed based on an inventory level approach. In fact, the reactive nitrogen quantification, which is the basis for the actual nitrogen footprint indicators, provides aggregate information regarding only nitrogen flows incoming and outgoing a product system. With reference to the framework of the proposed methodology (Figure 3.1), the reactive nitrogen accounting can be considered an intermediate output between inventory and assessment phases, as better explained in the following detailed description of the methodology. The attempt made with the new proposal is to process the output streams of the product systems by a phase of impact assessment in order to quantify the generated environmental impacts. Specifically, this process requires to associate inventory data with specific environmental impact categories and category indicators, thereby attempting to understand and to quantify these impacts.

This stage of the proposed methodology is borrowed from the life cycle impact assessment (LCIA) phase that includes the collection of indicator results for the different impact categories, which together represent the LCIA profile for the product system.

According to the requisite of ISO standards (ISO, 2006b), to which reference is made for a more detailed analysis, the following mandatory elements must be included in the LCIA phase:

- selection of impact categories, category indicators and characterization models;
- assignment of LCI results to the selected impact categories (classification);
- calculation of category indicator results (characterization).

Some elements should be emphasized as fundamental to the implementation of the model that will be illustrated in the following paragraphs, particularly as regards the environmental mechanism, that is the total of environmental processes related to the characterization of the impacts. In this concept is comprised the selection of characterization models which reflect the environmental mechanism by describing the relationship between the inventory results and category indicators. According to ISO indications (ISO, 2006b) the impact categories, category indicators and characterization models should be internationally accepted, i.e. based on an international agreement or approved by a competent international body; furthermore the characterization model for each category indicator should be scientifically and technically valid, and based upon a distinct identifiable environmental mechanism and reproducible empirical observation.

The core of the impact assessment is the characterization phase, whose aim is the calculation of indicator results involving the conversion of inventory results to common units and the aggregation of the converted results within the same impact category. This conversion uses the so called "characterization factors" to obtain a numerical indicator result. The usefulness of the indicator results for a given goal and scope depends on the accuracy, validity and characteristics of the characterization models and characterization factors.

3.1.3 Supporting tools for the development of the methodology

Before proceeding to the detailed definition of the new methodology, some preliminary issues need to be addressed, in relation to supporting tools that are essential requirements for the model implementation. These are typical support tools of the LCA applications judged to be indispensable for dealing with any LCA-type systematic approach: for this reason, they are briefly described in the following paragraphs, highlighting the most relevant elements for the subsequent description of the method.

3.1.3.1 Databases

As for any assessment tool, data is the primary material on which it is based any LCA application and consequently the proposed methodology. In particular, for the phase of inventory analysis, large amounts of process and production data are needed. Process units defined within the product system must be described in the most detailed manner as possible as regard the inputs and outputs of materials, energy, products, and releases to environment.

In general, data collection can be defined as the process of gathering data for a specific purpose. "Raw data" are data that have not been set in relation to the quantitative reference of the unit process dataset. Data gathering needs should be supported by the unit process dataset's mathematical relationships and by the goal and scope of the application. The following options for data collection exist, as data collection procedures or sources:

- Primary data can include:
  - interviews,
  - questionnaires or surveys,
  - bookkeeping or enterprise resource planning (ERP) system,
  - data collection tools (online, offline)
  - on-site measurements.
- Secondary data can include:
  - interviews,
  - statistics,

  - literature.
- Data generation can include:
  - calculations (e.g., missing emission factors from input data),
  - estimates.

For each unit process dataset, a combination of these options usually is applied; also, several techniques may be used in a sequence (Sonnemann *et al.*, 2013).

The data flow from the raw data providers to the end user consists of various activities and implies the interaction of various subjects, as represented in the Figure 3.3.

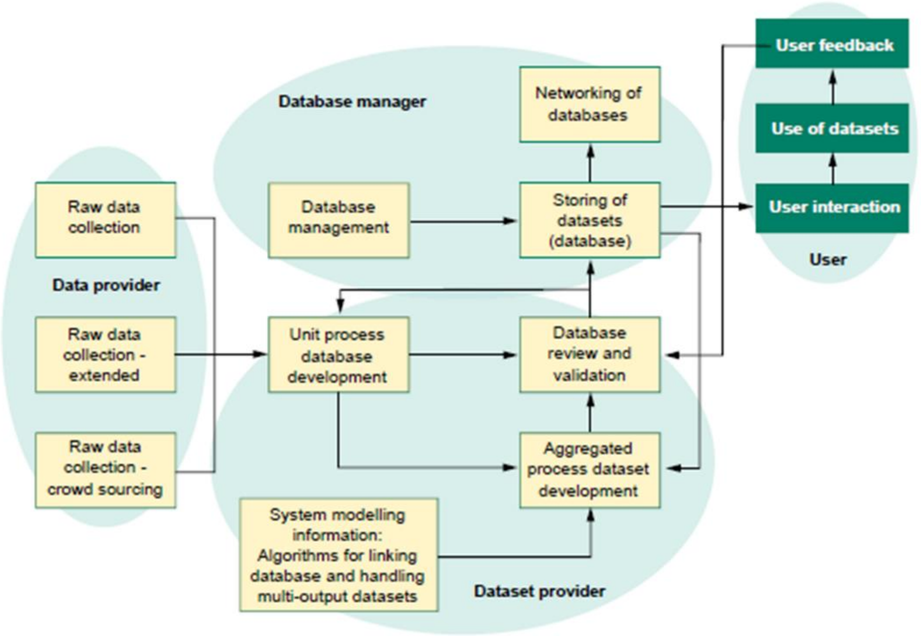


Figure 3.3. *Flow of data from raw data through to inventory data user with feedback loops and related subjects. Source: Sonnemann et al. (2013).*

Within this work, the perspective applied for the methodology description is that of the user, that is a person or organization responsible for building an assessment model from one or more unit process datasets or aggregated process datasets taken from one or more databases. The user may combine data from existing databases with those from his own investigations and is responsible for presenting and interpreting the assessment results and the resulting recommendations within a decision process. The user is not necessarily the decision maker. In that sense, users can be found within industry, government, consultancy and academia, whereas decision makers are primarily located in industry and governments.

Accessing and retrieving data for assessment studies is a complex issue that requires both economical and time-consuming resources. Adopting the point of view of the user, there are various ways to obtain useful data (Sonnemann *et al.,* 2013):

- interviews;
- questionnaires and surveys: these tools are similar to questionnaires but should include sampling of a process in addition to collection or extraction of data from process information;
- data collection tools (online, offline, software driven questionnaires): while having similar issues as questionnaires and surveys, these tools offer much better possibilities for automated consistency and completeness checks;
- measurements on site: in this case sampling time and sampling method (equipment, specific methodology) need to be selected according to goal and scope of the assessment;
- statistics;
- calculation;
- estimates;
- proxy unit process: in same cases a particularly useful data source is an existing similar (proxy) unit process, for example, a related technology or the same technology for another region or another time period. The unit process data for the proxy may be able to be used directly (e.g., use the same emission factor).

There is a general ranking of data collection methods (of the same quality):

I. measurements;
II. calculations;
III. estimations.

Estimates should be avoided, and if they cannot be avoided, they should be backed by measurements or by calculations, which then can be used as plausibility checks. The use of estimation to fill data gaps is useful even if the specific missing data cannot be measured, but other data are available and can then be used by relation to a common operation.

In most cases, the use of databases is indispensable for completing the inventory of an assessment. Different classifications of existing databases can be made: it is considered useful for the purposes of this work to distinguish between databases in which the data are specifically structured with an LCA approach – which could be called LCI (Life Cycle Inventory) data – and other databases which contains non-LCI data. It must be highlighted that the non-LCI data, like those made available by government document and database, albeit free, tend to be at least several years old. Furthermore, these data may be less specific and less accurate than, for example, industry data for specific facilities or data contained in commercial software tools for LCA applications. Another challenge to using non-LCI databases is the difficulty in aggregating facility data for the purpose of the assessment or the complexity of reconstructing lifecycle data from different sources with incompatible features as regards the format. An exhaustive presentation and analysis of existing database, free or for a fee, containing LCI and non-LCI data, is that carried out by Curran (2012) to which reference is made for further details.

3.1.3.2 Characterization models

Life Cycle Impact Assessment (LCIA) is defined by the standards (ISO, 2006a,b) as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system". The purpose of the impact assessment phase is thus to interpret the life cycle emissions and resource consumption inventory in terms of indicators evaluating the environmental impact. Several stages are included in the LCIA phase: some are classified as mandatory, others as optional, as represented in Figure 3.4.

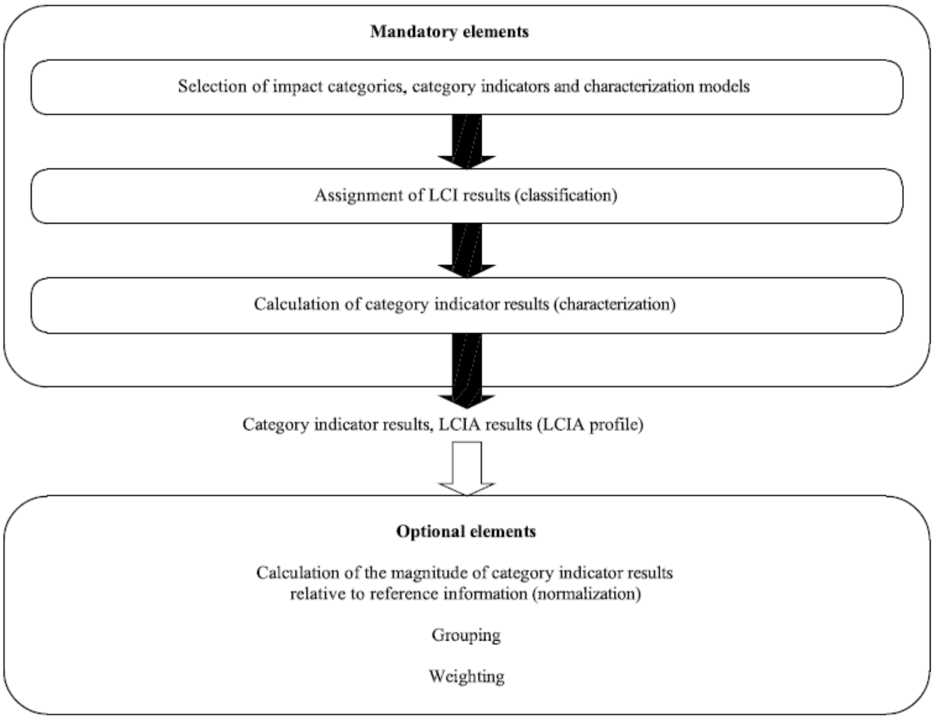


Figure 3.4. *Mandatory and optional elements of Life Cycle Impact Assessments phase. Source: ISO (2006a).*

In particular, characterization or "calculation of impact category indicator results" is identified as the mandatory third element of the life cycle impact assessment. It is the stage in which the potential impact from each inventory emission to – and/or resource flow from – the environment is modeled quantitatively according to the relevant environmental mechanism using a characterization model.

The characterization model calculates substance-specific characterization factors that express the potential impact of each single elementary flow in terms of the common unit of the category indicator. Characterization factors thus allow comparing the different elementary flows quantitatively in terms of their ability to contribute to the impact category indicator. The collection of individual characterization models (each addressing their separate impact category) is referred to as a "life cycle impact assessment (LCIA) method" (Hauschild *et al.*, 2013).

According to ISO 14044, the indicator of an impact category can be chosen anywhere along the impact pathway, which links inventory data to impacts on the final receptors or area of protection (AoP). With regard to this theme, a fundamental distinction is between:

- ***characterization at midpoint level,*** which models the impact using an indicator located somewhere along (but before the end of) the mechanism, and
- ***characterization at the endpoint level*** which requires modelling all the way to the impact on the entities described by the areas of protection (i.e. on human health, on the natural environment and on natural resources). This then allows for cross-comparison of different impact categories within AoPs on a natural or social science basis, and where possible taking into account all substance-specific differences.

Impact categories at the midpoint level are defined at the place where a common mechanism for a variety of substances within that specific impact category exists. For example, "Global Warming" impacts involve a series of steps, starting with the release of greenhouse gases, and ending with impacts on humans and ecosystems. There is a point where the greenhouse gases have an effect on the radiative forcing. Greenhouse gas emissions have a pathway that is different before that point, but identical beyond that point. Therefore, the radiative forcing provides a suitable indicator for the midpoint impact category of "Global Warming". Most of the other impact categories, such as "Human Toxicity" and "Ecotoxicity Effects" are more heterogeneous. In these impact categories there is no real midpoint. The midpoint applied is in fact as close as practicable to the area of protection (EC-JRC, 2010c).

The possibility of choice and trade-off between the use of a midpoint and an endpoint approach for modeling the assessment of impacts is a particularly debated issue. Curran (2012) highlights that on one hand, midpoint indicators are removed from observable or tangible impacts, making it harder for the public to relate to the indicator results. On the other hand, modeling to an endpoint introduces additional uncertainty as the location specific data become less certain and less available. For example, an indicator that accounts in terms of crop loss due to acid rain, although having a greater degree of uncertainty, is easier to understand for people rather than an indicator of the same impact that accounts in terms of potential increase in acidification, measured in hydrogen-ion equivalents.

An example of framework of characterization models, linking elementary flows from the inventory results to indicator results at midpoint level and endpoint level is reported in the Figure 3.5.

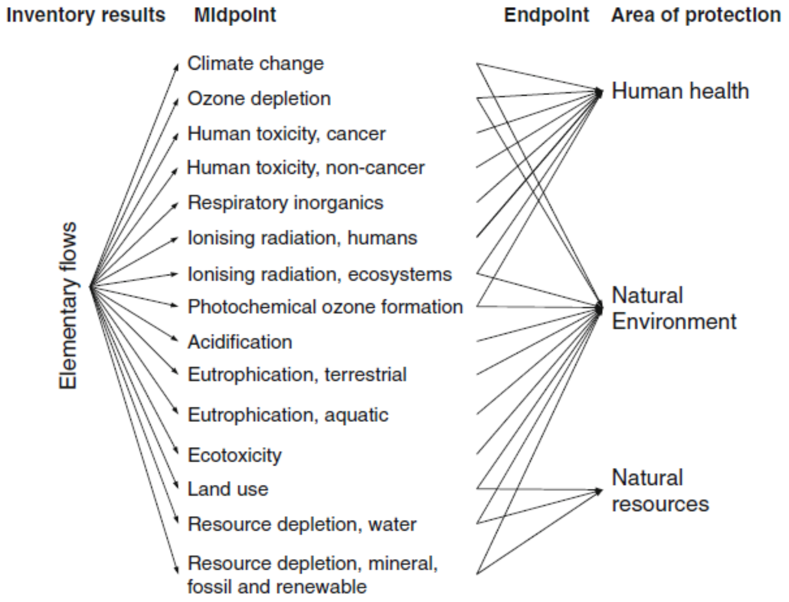


Figure 3.5. *Relationship between the midpoint impact categories and three Areas of Protection proposed by European Commission - Joint Research Centre (EC-JRC, 2010c).*

Entering more specifically in the theme of impact assessment modeling, it is clear that the credibility of the results obtained from an assessment depends largely on the validity of the characterization model used: in this regard, ISO (2006b) emphasizes that “the impact categories, category indicators and characterization models should be internationally accepted, i.e. based on an international agreement or approved by a competent international body”.

Attempts have been made in several working groups and task forces on life cycle impact assessment under the Society of Environmental Toxicology and Chemistry (SETAC) and later under the UNEP-SETAC Life Cycle Initiative, but they have not resulted in a uniform globally accepted set of characterization models and factors.

In parallel, serval life cycle impact assessment methodologies have been developed and applied, going from dedicated midpoint methodologies (eg. CML 2002, EDIP 2003, TRACI) and endpoint methodologies (eg. EPS, Ecoindicator) towards methodologies that try to combine the two approaches and model impacts at both midpoint and endpoint levels (eg. LIME, ReCiPe, IMPACT2002+).

In this context, the Joint Research Centre (JRC) of the European Commission has launched the International Reference Life Cycle Data System (ILCD) to develop technical guidance that provides the basis for greater consistency and quality of life cycle data, methods, and LCA studies. For this goal, an evaluation was also performed of existing LCIA methods and characterization models, both midpoint and endpoint level, with the aim to identify the best existing practice.

As anticipated, the impact assessment approach, inserted into a LCA logic, is a crucial point for the proposed methodology for nitrogen footprint accounting, and accordingly also the choice of appropriate characterization models. For this reason, starting from the JRC analysis, an initial evaluation of most used, within LCA applications, and scientifically recognized impact categories was made, in order to identify those connected in any way to the perturbation of the nitrogen cycle. The analysis resulted in the following impact categories, in which it turned out that elementary flows of nitrogen containing substances are taken into account, defining the related characterization factors:

- climate change;
- human toxicity, cancer effects;
- human toxicity, non-cancer effects;
- particulate matter formation;
- photochemical ozone formation;
- acidification;
- terrestrial eutrophication;
- marine eutrophication;
- freshwater ecotoxicity.

The first and most important difficulty in addressing the nitrogen footprint using an LCA perspective stems from the fact that, as is apparent from the list above, the environmental impacts related to the nitrogen cycle and derived from nitrogen-containing substances are numerous and affect different impact categories. A model for addressing quantification of nitrogen footprint, therefore, will need to consider different characterization models and elaborate results with a multi-criteria approach, as is normally the case for a full LCA application. From this point of view, addressing a nitrogen footprint model is much more complex than, for example, calculating a carbon footprint, which, according to the schemes currently applied, is based on a single impact category: climate change.

Several authors discussed the topic of emissions that relate to more than one impact category, concluding that this topic mainly relates to multiple impacts of chemical releases and distinguishing the following four categories of emissions (Guinée *et al.*, 2002):

- Emissions with parallel impacts, i.e. emissions of substances that may theoretically contribute to more than one impact category but in practice only to one, e.g. an emission of SO_2 which may have either toxic or acidifying impacts.
- Emissions with serial impacts, i.e. emissions of substances that may in practice have successive impacts, e.g. emissions of heavy metals which may first have eco-toxicological impacts and subsequently, via food chains, impacts on human health.
- Emissions with indirect impacts, i.e. emissions of substances having a primary impact that in turn leads to one or more secondary impacts, e.g. aluminium toxicity induced by acidification, or methane contributing to photo-oxidant formation, with the produced ozone contributing in turn to climate change, which in turn may contribute to stratospheric ozone depletion.
- Emissions with combined impacts, i.e. emissions of substances having a mutual influence on each other's impacts, e.g. synergistic or antagonistic impacts of toxic substance mixes, or NO_x and VOC, both of which are required for photo-oxidant formation.

As reported by Guinée (2015), in order to avoid double counting, for emissions having parallel impacts, it is generally recommended in the literature that the respective contributions of such emissions to relevant impact categories be specified. However, no guidelines are available on how this task is to be performed. In general, such specification should be performed only in those cases where it really matters (where the contribution of the substance to one impact category substantially lessens its potential contribution to another). If it is unclear how such emissions are to be allocated, they are often assigned in their entirety to all relevant impact categories.

For generally acknowledged and well-defined impact categories with a limited number of contributing flows, such as global warming/climate change, stratospheric ozone depletion, acidification and eutrophication, the default lists of emission and their classification into the impact categories are highly similar between different life cycle assessment methods.

Starting from these considerations and using the results of the JRC analysis (EC-JRC, 2010b; EC-JRC, 2011), to design the methodology, a selection was made in order to identify, for the previously listed impact categories, the best among existing characterization models. The results are shown in the Table 3.1, in which the best characterization models for each impact category are reported with related category indicators and classification by JRC expressed in three levels of recommendation.

Table 3.1. *Best available characterization models at midpoint recommended under the ILCD. The classification levels are the following: I – recommended and satisfactory; II – recommended but in need of some improvements; III – recommended, but to be applied with caution. Source: EC-JRC (2011).*

Impact category	Best among existing characterization models	Indicator	Classification
Climate change	Baseline model of 100 years of the IPCC (Forster et al., 2007)	Radiative forcing as global warming potential (GWP_{100})	I
Human toxicity, cancer effects	USEtox model (Rosenbaum et al., 2008)	Comparative toxic unit for humans (CTU_h)	II/III
Human toxicity, non-cancer effects	USEtox model (Rosenbaum et al., 2008)	Comparative toxic unit for humans (CTU_h)	II/III
Particulate matter - respiratory inorganics	Compilation in Humbert (2009) based on Rabl and Spadaro (2004) and Greco et al. (2007)	Intake fraction for fine particles (kg $PM_{2.5}$-eq/kg)	I/II
Photochemical ozone formation	LOTOS-EUROS as applied in ReCiPe (van Zelm et al., 2008)	Tropospheric ozone concentration increase	II
Acidification	Accumulated exceedance (Seppälä et al., 2006; Posch et al., 2008)	Accumulated exceedance (AE)	II
Eutrophication, terrestrial	Accumulated exceedance (Seppälä et al., 2006; Posch et al., 2008)	Accumulated exceedance (AE)	II
Eutrophication, aquatic	EUTREND model as implemented in ReCiPe (Struijs et al., 2009 in Goedkoop et al., 2009)	Residence time of nutrients in freshwater (P) or marine end compartment (N)	II
Ecotoxcity (freshwater)	USEtox model (Rosenbaum et al., 2008)	Comparative Toxic Unit for ecosystems (CTU_e)	II/III

As can be seen, the investigation was limited to the midpoint characterization models, as more suitable for the purposes of the proposed methodology, as well as more scientifically recognized, for the fact that, as noted above, they introduce less uncertainty in the final assessment output.

A detailed description of the characterization methods above reported and used in the proposed methodology is reported in the Appendix A.

3.1.3.3 Normalization and weighting

From the application characterization models is obtained, as a result, an impact assessment profile showing the environmental impacts in several impact categories. For the proposed methodology, typically, will be obtained a profile composed by the results of the previously listed nine impact categories, or consisting of a smaller number of categories if no result can be attributed to one or more categories (for example, if inventory results do not show any emissions related to a specific impact category). The profile thus obtained is a valid result for a complete assessment of the impacts associated with the nitrogen cycle: similarly to what was seen for LCA, the calculation of category indicator results (LCIA profile), is the last mandatory element of the methodology according to the ISO standards.

Subsequent operations, such as normalization and weighting, which are considered optional elements in an LCA application, can become crucial for comparing different alternatives and necessary for achieving a single score as result of the assessment. It could be difficult, in fact, to make an evaluation of the overall environmental impact of an entity or of alternatives based on multiple criteria with units of measurement not comparable (e.g., kg CO_2 eq., kg $PM_{2.5}$ eq. and kg N eq.). Furthermore, in operating a comparison between environmental performances of different alternatives, it is rare to find an alternative that outperforms the others in all the analyzed impact categories. Rather, the most common case is to find alternatives which perform differently in the selected impact categories, thus making normalization and weighting necessary tools for comparative assessments.

As defined by the ISO standards (ISO, 2006b), ***normalization*** is the calculation of the magnitude of the category indicator results relative to some reference information. The aim of the normalization is to understand better the relative magnitude for each indicator result of the product system under study. It is an optional element that may be helpful in, for example:

- checking for inconsistencies,
- providing and communicating information on the relative significance of the indicator results, and
- preparing for additional procedures, such as grouping, weighting or life cycle interpretation.

Normalization transforms an indicator result by dividing it by a selected reference value. Some examples of reference values are:

- the total inputs and outputs for a given area that may be global, regional, national or local,
- the total inputs and outputs for a given area on a *per capita* basis or similar measurement, and
- inputs and outputs in a baseline scenario, such as a given alternative product system.

As reported by Sala *et al.* (2015), results of several normalization efforts are available to date: in particular, they were developed and found to be applied within the LCA studies. Just to name a few, a set of normalization factors for US based on TRACI as life cycle impact assessment (LCIA) method was developed by Bare *et al.* 2006. Normalization references for European and the global economic systems, considering 15 different impact categories for the year 2000, were produced by Sleeswijk *et* *al.* (2008). Laurent *et al.* (2011) developed normalization references for Europe and North America referring to USEtox (Rosenbaum *et al.*, 2008) impact categories. Lautier *et al.* (2010) focused on the calculation of normalization references for North America with reference to the IMPACT2002+ (Jolliet *et al.*, 2003) LCIA method.

In the context of this work, was chosen as the reference set, for its credibility at the scientific level in Europe, that recommended by the JRC (Benini *et al.*, 2014) providing normalization factors also for the implementation of the EU Product Environmental Footprint methodology (European Commission, 2013). **S**pecifically, the JRC calculation of normalization factors for the Product Environmental Footprint, was based on a refinement and update of the ‘Life Cycle indicators for Resources’ dataset (European Commission, 2012), used as inventory. This dataset was developed with the aim to monitor the environmental impacts associated with European production and consumption, as well as waste management within the EU, by including also impacts from trade (imports and exports).

According to the approach adopted for the ‘Life Cycle Indicators for Resources’ dataset (LC Indicators) and for the consequent set of normalization factors, the impacts associated with the imported products were summed to the impacts related to the activities taking place in the EU-27 territory (domestic), minus the impacts associated to the exported products. In detail, the total environmental impact, according to LCA methodologies, was calculated in two steps: building of life cycle inventory and characterizing of the inventory. Regarding the life cycle impact assessment, the ILCD recommended impact assessment methods (EC - JRC, 2011) and the related characterization factors (Sala *et al.,* 2012) were used for calculating the normalization factors. The results obtained, are reported in Table 3.2, limiting the scope only to the impact categories related to the nitrogen cycle, as identified in the previous paragraph.

Table 3.2. *Recommended normalization factors according to JRC indications for nitrogen-related impact categories. Per person normalization factors have been calculated using Eurostat data on the EU-27 population in 2010: 499 million inhabitants. Extracted from Benini et al. (2014).*

Impact category	Unit	Domestic	Normalisation factor per person (domestic)	Overall robustness
Climate change	kg CO_2 eq.	4.60E+12	9.22E+03	Very High
Human toxicity, cancer effects	CTU_h	1.84E+04	3.69E-05	Low
Human toxicity, non-cancer effects	CTU_h	2.66E+05	5.33E-04	Low

Impact category	Unit	Domestic	Normalisation factor per person (domestic)	Overall robustness
Particulate matter - respiratory inorganics	kg $PM_{2.5}$ eq.	1.90E+09	3.80E+00	Very High
Photochemical ozone formation	kg NMVOC eq.	1.58E+10	3.17E+01	Medium
Acidification	mol H^+ eq.	2.36E+10	4.73E+01	High
Eutrophication, terrestrial	mol N eq.	8.76E+10	1.76E+02	Medium
Eutrophication, marine	kg N eq.	8.44E+09	1.69E+01	Medium to Low
Ecotoxcity for aquatic fresh water	CTU_h	4.36E+12	8.74E+03	Low

It is considered important to emphasize that the above reported normalization factors are also recommended within the studies and applications developed by the European Union under the Sustainable Consumption and Production Action Plan, in particular with reference to the “Guidance for the implementation of the EU Product Environmental Footprint (PEF) during the Environmental Footprint (EF) pilot phase” (European Commission, 2014).

Again according to ISO standards (ISO, 2006b), ***weighting*** is the process of converting indicator results of different impact categories by using numerical factors based on value-choices. It may include aggregation of the weighted indicator results. Weighting is an optional element with two possible procedures, either:

- to convert the indicator results or normalized results with selected weighting factors, or
- to aggregate these converted indicator results or normalized results across impact categories.

Issues related to weighting and weighting factors are highly debated among LCA researchers and experts. Among the others, Prado *et al.* (2012) stated that the weighting process help to simplify tradeoffs when dealing with competing alternatives and opposing values within a panel of decision makers. Weighting, furthermore, allows for impacts to be aggregated into a single score for easier evaluation. However, weights are inherently subjective and can vary depending on culture, political views, gender, demographics, and professional opinion of stakeholders. Consequently, single-score results are criticized by some practitioners.

Regarding the weighting factors, Ahlroth *et al.* (2011) evidenced a lack of consistent weighting/valuation sets, stressing that in many existing weighting sets, different types of impacts are valued with different methods, which make them inherently incomparable. These same authors proposed a taxonomy for valuation and weighting methods used in some selected "Environmental Systems Analysis Tools" – among which LCA is also considered – as listed below:

- ***Monetary valuation methods***:
    - Revealed willingness to pay (e.g. Market prices, Revealed preference methods, Productivity method, Travel cost, Hedonic pricing);
    - Expressed willingness to pay (e.g. Stated preference methods, Contingent valuation, Choice modelling);
    - Imputed willingness to pay (e.g. Damage cost avoided method, Replacement Cost Method, Substitute Cost Method);
    - Political willingness to pay (e.g. Costs-to-reach-target, Taxes);
    - Avoidance costs;
- ***Non-monetary weighting methods:***
    - Proxy methods (e.g. Ad hoc scoring, Indicators in physical units as TMR, energy requirements, Ecological footprints);
    - Distance-to-target methods
    - Panel weighting methods (e.g. ad hoc methods using expert assessments, stakeholders, etc., Multi-criteria analysis).

Focusing on weighting procedures usually adopted within LCA approach, is once again the JRC offering a classification of the weighting methods and identifying three main categories (Huppes and van Oers, 2011):

- ***Midpoint modelling and evaluation***. The midpoint weighting method refers to midpoint impact categories like climate change and acidification. Here, assumptions on further empirical effects towards endpoints and their evaluation are combined in one step.
- ***Endpoint modelling and evaluation***. The endpoint method converts interventions into damages at endpoint levels. These endpoints, as in terms of damages to human health and biodiversity, are subsequently evaluated in a weighting step to aggregate the endpoint scores.
- ***Integrated modelling and evaluation***. Is a method developed by economists thus, compared to the previous methods, builds upon a different, yet very relevant domain. The economic method is based on willingness to pay (WtP), as estimated through general panel procedures. A number of different economic approaches exist, covering different types of environmental interventions.

As again highlighted by Huppes and van Oers (2011), in general, the midpoint evaluation has the most robust modelling, but only to midpoint level. Endpoint models are based on midpoint models, thus they add extra uncertainty on top of the uncertainty already affecting midpoint evaluations by modelling further to the endpoints, whilst also providing additional information. This can reduce the need to use social/economic values to cross-compare impacts at the end-point level, such as in terms of human health, ecosystem impacts, etc.

By way of example, it is considered useful to report, in the Table 3.3, three reference weighting sets, based on a panel procedure: the weighting factors are given for 9 to 13 midpoint impact categories, depending on the method.

Table 3.3. *Weighting factors [%] of three panel weighting sets: EPA Science Advisory Board (Lippiatt, 2007), BEES Stakeholder Panel (Lippiatt, 2007), NOGEPA (Huppes et al., 2007) as reported by Huppes and van Oers (2011).*

ILCD recommended midpoint impact categories	**Impact category on midpoint level**	**Panel weighting set [%]**		
		EPA Science Advisory Board	**BEES Stakeholder Panel**	**NOGEPA**
Climate change	Climate change	16	29	32
Ozone depletion	Ozone depletion	5	2	5
Acidification	Acidification	5	3	6
-	Eutrophication	5	6	13
Eutrophication, terrestrial	-	-	-	-
Eutrophication, fresh water	-	-	-	-
Photochemical ozone formation	Photochem. ozone form.	6	4	8
-	Hum. health-non canc.	11	-	16
Human toxicity – cancer effects	Hum. health-canc.	-	8	-
Human toxicity - non-cancer effects	Hum. health-non canc.	-	5	-
Particulate matter/Respir. inorg.	Hum. health criteria pollut.	6	9	-
-	Ecotoxicity	11	7	-
Ecotoxicity – fresh water	Fresh water ecotoxicity	-	-	6
-	Marine ecotoxicity	-	-	8
-	Terrestrial ecotoxicity	-	-	5
Ionizing radiat., hum. health effects	-	-	-	-
Ionizing radiation, ecosystems	-	-	-	-
Resource depl. (min., foss. renew.)	-	-	-	-
-	Resource depl. (fossil fuel)	5	10	-
Resource depletion water	Water intake	3	8	-
-	Indoor air quality	11	3	-
Land use	Habitat alteration	16	6	-
	Total	**100**	**100**	**100**

Again, the midpoint impact categories recommended by the JRC within the ILCD Handbook (EC - JRC, 2011) were used as a reference: it is worth to note that the midpoint impact categories considered by the reported weighting sets, comply not completely, albeit to a large extent, with the ILCD framework. In fact, as noted by Huppes and van Oers (2011), some operational weighting sets miss weighting factors for some of the draft ILCD recommended impact categories. For example, on the midpoint level the NOGEPA weighting set does not cover ionizing radiation, land use and (abiotic) resource depletion. The BEES weighting set lacks weighting factors for ionizing radiation. On the other hand, also weighting factors might be available for impact categories that are not part of the recommended ILCD impact assessment. For example, on the midpoint level, the BEES weighting set has a superfluous factor for the work environment. For this reason, in order to fully comply with ILCD impact assessment categories, the same authors proposed a modification of the weighing sets presented in the Table 3.3, together with an additional set consisting of the average value of the three modified weighting sets (EPA, BEES, NOGEPA): this last set is reported in the Table 3.4 (first column).

Starting from this average set, the values of specific weighting coefficients were calculated, limiting the scope to the only nine impact categories related to the nitrogen cycle: the calculation was done by reporting to 100 the value of the nine selected weighting factors, as shown in Table 3.4.

Table 3.4. *Weighting factors [%] for ILCD recommended midpoint impact categories. Set on the left: average of modified EPA, BEES and NOGEP as proposed by Huppes and van Oers (2011). Set on the right: specifically adpted (based on the left) within this work for the only nitrogen related impact categories.*

ILCD recommended midpoint impact categories	**Weighting set [%]**	
	Average set EPA BEES, NOGEPA set	**Calculated set for nitrogen-related impact categories**
Climate change	23	35.6
Ozone depletion	4	-
Acidification	4	6.2
Eutrophication	7	-
Eutrophication, terrestrial	(7/3)	3.6
Eutrophication, fresh water	(7/3)	-
Eutrophication, marine	(7/3)	3.6
Photochemical ozone formation	5	7.7
Human toxicity – cancer effects	6	9.3
Human toxicity - non-cancer effects	4	6.2
Particulate matter / Respiratory inorganics	7	10.8
Ecotoxicity	11	17.0
Ionizing radiation, human health	6/2	-
Ionizing radiation, ecosystems	6/2	-
Resource depletion	7	-
Resource depletion water	5	-
Land use	10	-
Total	**100**	**100**

The calculated set above reported is one solution for a weighting set, based on an external panel evaluation and applicable to the nitrogen impact assessment: other solutions, based on internal data derived from the analyzed product system or on data derived from a product system created ad hoc for the purposes of this work, are presented in the following sections.

For completeness it must also be mentioned the possibility to use a system of equal weighting as also reported within the guidance for calculating and reporting products' life cycle environmental impacts issued by European Union (European Commission, 2016): in the guidance is recommended that all impact categories receive the same weight (weighting factor = 1), until there is an agreed set of European weighting factors.

3.1.3.4 Software

A usual LCA application requires accounting data about several processes and their input and output flows, managing the connections between processes, balance calculating, impact assessing, normalizing and weighting. The management of data and calculations related to the inventory, impact assessment and interpretation phase would be not possible without the support of an appropriate software. For LCA applicators software is the tool that, in synthesis, converts data into a model, providing results to be used, generally, in decision support.

Among the different features that the software offer, is worth mentioning the availability of several specific databases, different characterization, normalization and weighting methodologies and uncertainty calculation tools, the possibility to graphically represent product systems and incoming and outgoing streams, as well as, of course, the ability to efficiently and quickly process data, allowing rapid changes and comparisons.

In order to present typical characteristics of currently available software, some possible categorizations are summarized below, as formulated by Curran (2012):

- ***Web or desktop tools.*** Hand in hand with the spread of online tools, LCA software, traditionally locally installed on a desktop, have begun to be installed on a web server, and remote accessed by users. Online tools usually offer a clean, modern and therefore attractive user interface. Furthermore, they need to be installed only once, this being an advantage for larger companies ore large user groups; finally, data and software updates can be centrally managed. On the other side, in the web tools, the local user has less control over software and data, and typically also over the server where the software is running and therefore might be reluctant to upload sensitive data to a web server difficult to control. Also, handling large amounts of data, requires careful optimization even with modern, fast connections, and is still posing challenges to web applications.

- ***Commercial or freeware tools.*** Several commercial tools are in the market since years, widely used by applicants; yet still, some tools have always been freely available. These tools usually do not offer all features of commercial systems; workflow and user interface design do not always comply with user interface conventions. More advanced features, as the graphical visualization of supply chains, and in depth result and contribution analysis may be lacking. On the other side, some more advanced and special, rather experimental methods may be available in free tools.
- ***Open or closed source.*** Open source software is released under a specific open source license whose main feature is the fact that the source code of the software is available free of charge for everyone. Besides being free, the software is fully transparent and can be updated and modified directly by the user. For the creator of the software, a broad range of other open source tools is available that can be combined or adapted to fit to the own software; this allows building more mature and feature-rich systems relatively fast.
- ***General, specialized or add-ons tools.*** General tools are intended as full modeling systems that offer users all features required for performing complete LCA applications. There are also specialized tools for example for managing, specific data sets, editing particular data format, converting data from different formats. Then, there are tools targeting only a specific user group, created in dedicated research projects, providing in some cases a specific technical language for the targeted users. Finally, closely related to the last group, are software add-ons that provide some LCA calculation or modeling features as add-on to software that is used mainly for other purposes.

3.2 Proposal of new methodology for nitrogen footprint assessment

Starting from the considerations of the previous paragraphs and using the presented underlying general framework (§ 3.1.1), a methodology has been designed with the aim of providing a framework for comprehensive assessment of nitrogen-related impacts, applying a life cycle approach and adapting schemes, tools and methods typically used in the LCA applications.

The proposed methodology consists of two corollary “conceptual” phases:

- goal and scope definition,
- interpretation of the results,

and four methodologically operational steps:

- inventory analysis,
- assessment at inventory level,
- impact assessment (characterization),
- impact assessment (normalization and weighting).

The proposed methodology is schematically represented as a diagram in the Figure 3.6.

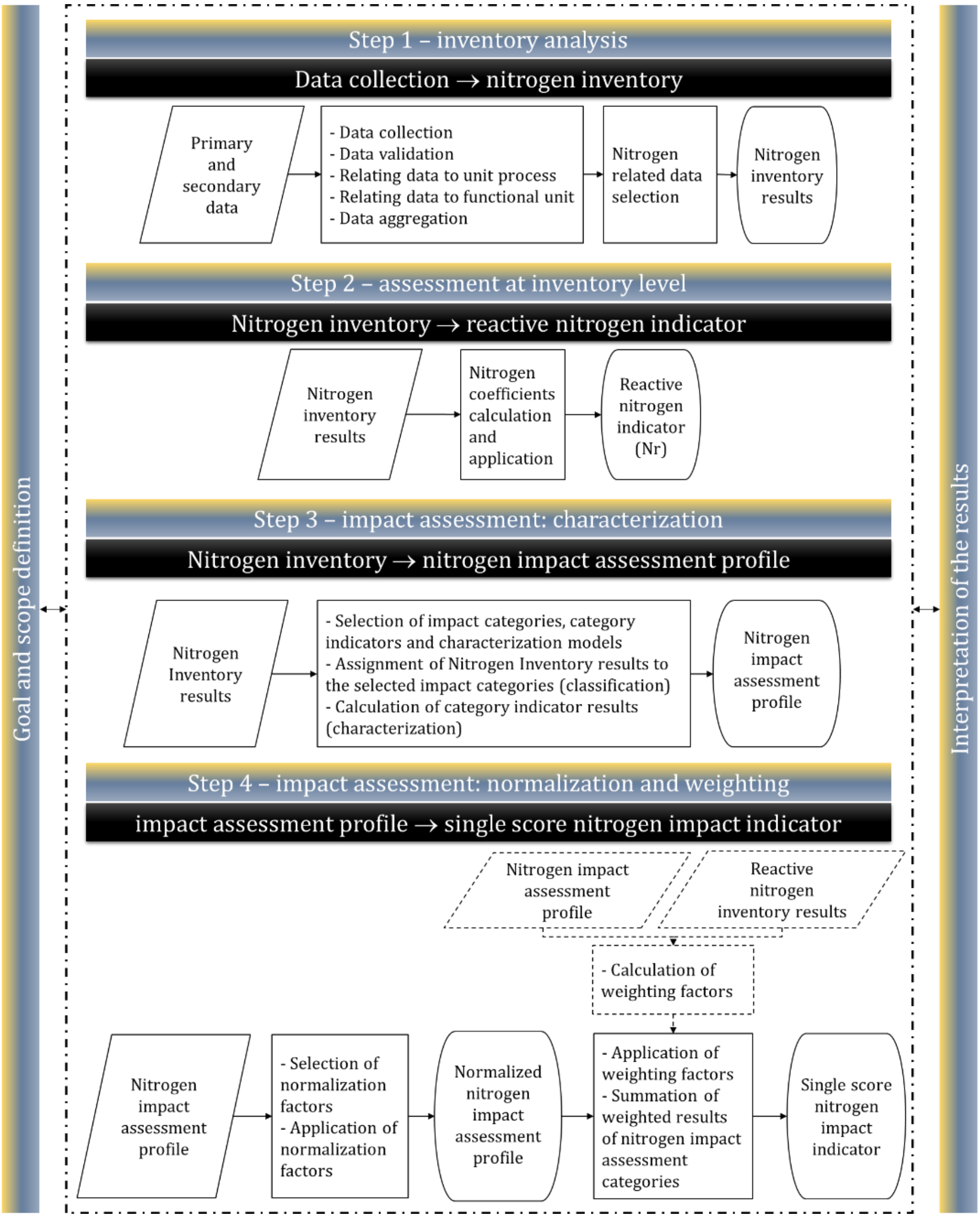


Figure 3.6. *Sheme of the proposed methodology for nitrogen footprint assessment*

The methodology has been designed to be applied both sequentially from the beginning phase (goal and scope definition) to the final phase (interpretation of the results) and selectively, by choosing which specific step is suitable to guarantee the expected application results. In fact, every single step actually produces a concrete result, which can be used as a tool for nitrogen-related impact assessment applications, depending on the specific goal and scope defined. According to this logic, only the corollary phases of goal and scope definition and interpretation of the results and the initial step of data collection must mandatorily be carried out. As for the other steps, these can be considered optional, however taking into account that the initial step of data collection, which provides the nitrogen inventory results, constitutes the starting point for the other steps, and therefore it must be firstly performed to obtain any ulterior result.

The phases and steps of the proposed methodology are presented in detail in the following paragraphs**.**

3.2.1 Goal and scope definition

The premise phase of ***goal and scope definition*** centers around formulating the questions related to the application objectives and stating the context of answering to these questions. In this step, the plan of the assessment is defined as clearly and unambiguously as possible, dealing with topics as the intended application, the reason for carrying out the assessment, the intended audience, the willingness to use the results for comparative assertions, etc. The scope definition also provides the setting of the product system, including the function and the functional unit. Due to the iterative nature of the proposed methodology, the scope may have to be refined during the application: in some cases, in fact, the goal and scope may be revised due to unforeseen limitations, constraints or as a result of additional information obtained.

3.2.2 Nitrogen inventory analysis

As stated, the proposed methodology has been based on the structure of the LCA and therefore the ***inventory analysis*** step is borrowed from what is contemplated for the LCA applications and required by the reference standards.

In particular, the nitrogen inventory step derives from the definition of the goal and scope phase, which provides the initial plan for conducting the inventory. This step, in turn consists of a series of operations as listed below (ISO, 2006b):

- ***Data collection.*** Through this operation, the qualitative and quantitative data for inclusion in the inventory shall be collected for each unit process that is included within the system boundary.

The collected data, whether measured, calculated or estimated, are utilized to quantify the inputs and outputs of a unit process.

- ***Data validation.*** A check on data validity shall be conducted during the process of data collection to confirm and provide evidence that the data quality requirements for the intended application have been fulfilled. Validation may involve establishing, for example, mass balances, energy balances and/or comparative analyses of release factors. Obvious anomalies in the data resulting from such validation procedures require alternative data that comply with the data selection.
- ***Relating data to unit process and functional unit.*** An appropriate flow shall be determined for each unit process. The quantitative input and output data of the unit process shall be calculated in relation to this flow. Based on the flow chart and the flows between unit processes, the flows of all unit processes are related to the reference flow. The calculation should result in all system input and output data being referenced to the functional unit.
- ***Data aggregation.*** Care should be taken when aggregating the inputs and outputs in the product system. The level of aggregation shall be consistent with the goal of the study. Data should only be aggregated if they are related to equivalent substances and to similar environmental impacts.

During the data collection stage, it may be necessary to perform allocation operations aimed at partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems. In particular, the inputs and outputs shall be allocated to the different products according to clearly stated procedures ensuring that the sum of the allocated inputs and outputs of a unit process is equal to the inputs and outputs of the unit process before allocation. The requirements for allocation procedures are the same as for the LCA methodology contained in the reference standards to which reference is made (ISO, 2006a,b).

The above operations should be conducted as in a normal LCA study, thus obtaining a complete inventory of incoming and outgoing flows from the analyzed product system. Although the object of analysis is subsequently to be limited with reference to the nitrogen cycle, it is however considered appropriate to conduct a complete data collection for different reasons set out below:

- it is almost certainly impossible to carry out an analysis with a LCA approach without resorting to external databases which are built to provide complete inventories: any primary data collected will therefore need to be integrated with data from databases and it is advisable to ensure as far as possible the compatibility and homogeneity between data;
- it may be necessary to make subsequent revisions of the data adding unexpectedly excluded information which would not be available by making a partial data collection;

- data outside the scope of nitrogen analysis may be useful for inferences and analyses related to the scope of the application;
- it may be necessary, at a later time, to extend the goal and scope of the application to include evaluations outside the restricted scope of the nitrogen impact assessment.

Once completed the inventory analysis, it is necessary to proceed to select the data related to the nitrogen impact analysis: from an operational point of view, this step consists in a selection of the results of the full inventory, in order to identify only the incoming and outgoing streams of nitrogen-containing substances attributed to the system.

In order to operate this selection, the main commercial databases used in the LCA applications were analyzed, with particular reference to specific databases for the agricultural and food sectors for which interactions are more likely to occur with the nitrogen cycle.

The contents of databases such as Ecoinvent 3 (http://www.ecoinvent.org/; Moreno Ruiz *et al.*, 2014), Agri-footprint (http://www.agri-footprint.com/; Durlinger *et al.*, 2014) and LCA Food DK (http://gefionau.dk/lcafood/) were therefore analyzed in order to identify a set of nitrogen-containing substances and compounds for which it is more probable to detect incoming and outgoing flows from the product systems to be analyzed.

The inventory analysis results must then be synoptically compared with the set of substances identified as above, in order to select the nitrogen containing substances constituting the nitrogen inventory results, that is the first output of the proposed methodology.

In particular, the results of the inventory analyzes carried out within this work, allowed to identify a set of about 200 nitrogen-containing substances and compounds: an automated selection procedure was then drawn up and tested as best described in the following paragraph.

3.2.3 Reactive nitrogen indicator accounting

Within the proposed methodology, the first step towards assessment of environmental impacts related to nitrogen cycle is the reactive nitrogen quantification for the product system, similarly to what is provided by the actual definition of nitrogen footprint. However, unlike what has been found to date in applications for nitrogen footprint accounting, the proposed methodology is structured in order to apply an operative LCA approach for the reactive nitrogen calculation, starting from inventory results that have already been obtained according to the LCA approach. In particular, considering the inevitable use of LCA structured databases for the proposed methodology, the innovative approach consists in making use, together with the primary data, of these databases, recognized at international level and shared by LCA practitioners, for the calculation of the reactive nitrogen.

The above-mentioned databases, in accordance with the requirements for inventory analysis, are designed to provide quantification of incoming and outgoing streams from the described product system. Comparing the structure of the inventory results and of the databases with the current definition of nitrogen footprint as "the total amount of reactive nitrogen released to the environment as a result of an entity's resource consumption, expressed in total units of N_r" (Leach *et al.*, 2012), a first problem found was to derive the streams of reactive nitrogen. In fact, if on one hand databases and usually primary data do not contain information relating to output flows of reactive nitrogen, on the other side, they do not even contain reliable data relating to the nitrogen incoming flows from which it could be possible to calculate the outputs by applying appropriate mass balances. This is probably because nitrogen, as atmospheric nitrogen reserve, is considered a potentially infinite resource and therefore the impacts due to its depletion are not considered within the scope of life cycle impact assessment, as is traditionally done, on the contrary, for example for metals and more recently for water.

To overcome this problem, starting from the output results of the inventory in terms of nitrogen-containing substances and compounds, an innovative approach has been developed to calculate the amount of reactive nitrogen of substances, in analogy with what was proposed by Pelletier and Leip (2014). In particular, the procedure involves calculating a nitrogen coefficient (Nc) for each nitrogen-containing substance or compound resulting in output from the analyzed product system, according to the following:

$$nitrogen\ coefficient\ (Nc_i) = \frac{molar\ mass\ of\ N\ contained\ in\ the\ substance/compound\ i}{molar\ mass\ of\ the\ substance/compound\ i} \ . \qquad (3.1)$$

In some specific cases highlighted below (for example for emissions of particulate matter), the 3.1 could not be used and some assumptions had to be made to calculate the nitrogen coefficient.

Starting from the coefficients thus obtained, the reactive nitrogen indicator is then defined as the total reactive nitrogen released by the product system, according to the following:

$$total\ reactive\ nitrogen\ (N_r) = \sum_{i=1}^{n} \sum_{j=1}^{m} s_{i,j} * f_{i,j} * Nc_{i,j} \quad [\frac{kg}{functional\ unit}] \ , \qquad (3.2)$$

where:

- *N_r is the reactive nitrogen indicator calculated for the whole product system;*
- *$s_{i,j}$ is the emitted amount of the i substance in the j compartment as resulting from inventory analysis [emission unit/functional unit];*
- *$f_{i,j}$ is the conversion factor for the homogenization of the results depending on the unit of measure used for the amount of the emitted substance [kg/emission unit of measure]: it will be considered implicit in the next equations;*
- *$Nc_{i,j}$ is the nitrogen coefficient for the substance/compound i in the j compartment (the nitrogen coefficient Nc_i of the i substance is the same for all j compartments, except for nitrogen emissions, as specified below: $Nc_{i,j}=0$ for nitrogen-non containing substances);*
- *i is the identification index of the specific substance/compound;*
- *j is the identification index of the substance compartment of emission;*
- *n is the total number of nitrogen-containing substance and compound for the product system;*
- *m is the total number of the compartments of emission (for this study m=3; the considered compartments are: air, water, soil).*

It is important to note that, for the purposes of this work, the result of this step has been defined as “reactive nitrogen indicator” and not as “nitrogen footprint” because it provides information only at inventory level, related to the reactive nitrogen streams and not information at impact level, related to the environmental impacts caused by these streams. Similarly, following the requirements of LCA methodology, it was preferred not to use the term “characterization factor” (as done by Pelletier and Leip, 2014) for the nitrogen coefficient defined in 3.1. In fact, these factors do not allow to quantify an effective impact indicator result for a defined impact category, but rather to aggregate the inventory results into a single indicator: exactly the reactive nitrogen. The latter may surely constitute a rough estimate of the product system impact related to the nitrogen cycle, but does not provide specific information on the typology and magnitude of the single potential environmental impacts attributable to the product system. In fact, at the basis of a presumed characterization model in terms of reactive nitrogen, is not defined a single precise and scientifically recognized environmental mechanism describing the interactions of nitrogen with environment. Rather, as shown in the initial chapters, there are different types of potential environmental impacts, in different environmental compartments, acting with different mechanisms. In ordere to better explain this concept, it is also considered useful to refer to the definition of life cycle impact assessment, which, according to the ISO standards (ISO, 2006b) is the “phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product”. The reactive nitrogen indicator, which, according to the current meaning, account for the nitrogen footprint, actually provides a quantification of an impact magnitude, but is unclear with regard to the significance of the impacts, which is provided only in aggregate and implicit form.

The approach proposed for the calculation of the nitrogen coefficients and reactive nitrogen indicator was firstly applied to 12 product systems of the agri-food sector (barley, rice, maize, soybean, tomato, potato, sugar beet, full milk, beef fillet, chicken, pork, sheep and egg). This choice was made starting from two considerations:

- the agri-food sector, along with the energy sector, is the one that provides the greatest contribution in terms of nitrogen related environmental impacts;
- the nitrogen footprint applications found in literature, to date, are for the most part related to agri-food products: some of these have been used as a comparison for a first validation of the methodology, as illustrated in the next chapter of this work, in which some applications of the proposed methodology are described.

This first application allowed determining the nitrogen-containing substances most likely to be found as output from inventory analysis and to calculate the corresponding nitrogen coefficients.

Table 3.5 shows the results of the calculation of nitrogen coefficient for more than 200 substances and compounds, obtained as output from the inventory analysis of the 12 product systems above described and of other applications carried out within this work, using Ecoinvent 3, Agri-footprint and LCA Food DK databases. In particular, for the inventory analysis of the 12 product systems of the agri-food sector, the substances for which to calculate the coefficients were selected applying a mass cut-off criterion according to which all outputs were considered whose mass was ≥ 1 ng for a reference unit of 1 kg of product.

For each selected substance or compound reported in the Table 3.5, the compartments of emission are listed, that are all the potentially compartments considered into the databases in which the substance is accounted as output stream. For each substance or compound, the molar mass, the number of nitrogen atoms contained in the molecule and the mass of nitrogen content are then reported. For the determination of the composition of substances and of the molar mass, the PubChem open database (Kim *et al.*, 2015; https://pubchem.ncbi.nlm.nih.gov/) was used.

Table 3.5. *Nitrogen coefficient (Nc) calculated for about 200 nitrogen containing substances and compounds obtained as output from the inventory analyzes carried out within the present work using databases Ecoinvent 3, Agri-footprint and LCA Food DK. Source for determination of chemical formula and molar mass: PubChem (Kim et al., 2015).*

Substance/Compound	**Compartment**	**Molar mass [g/mol]**	**Nitrogen atoms**	**Nitrogen content [g/mol]**	**Nc - Nitrogen coefficient**
1-Amino-2-propanol	air, water, soil	75.111	1	14.007	0.186
2-Aminopropanol	air, water	75.110	1	14.007	0.186
2-Nitrobenzoic acid	air	167.120	1	14.007	0.084
Acephate	air, water, soil	183.200	1	14.007	0.076
Acetamide	air, water, soil	59.070	1	14.007	0.237
Acetochlor	air, water, soil	269.767	1	14.007	0.052
Acetonitrile	air, water, soil	41.050	1	14.007	0.341
Acifluorfen	air, water, soil	361.660	1	14.007	0.039
Aclonifen	air, water, soil	264.670	2	28.013	0.106
Acrylonitrile	air, water, soil	53.064	1	14.0067	0.264
Alachlor	air, water, soil	269.767	1	14.007	0.052
Aldicarb	air, water, soil	190.263	2	28.013	0.147
Amidosulfuron	air, water, soil	369.375	5	70.034	0.190
Ammonia	air, water, soil	17.031	1	14.007	0.822
Ammonia, as N	water	14.007	1	14.007	1.000
Ammonium carbonate	air	96.090	2	28.013	0.292
Ammonium, ion	air, water, soil	18.040	1	14.007	0.776
Aniline	air, water, soil	93.129	1	14.007	0.150
Anthranilic acid	air	137.138	1	14.007	0.102
Antimycin A	air, water, soil	548.633	2	28.013	0.051
Asulam	air, water, soil	230.238	2	28.013	0.122
Atrazine	air, water, soil	215.680	5	70.034	0.325
Azinphos-methyl	air, water, soil	317.318	3	42.020	0.132
Azoxystrobin	air, water, soil	403.394	3	42.020	0.104
Benfluralin	air, water, soil	335.283	3	42.020	0.125
Benomyl	air, water, soil	290.323	4	56.027	0.193
Bensulfuron methyl ester	air, water, soil	410.401	4	56.027	0.137
Bentazone	air, water, soil	240.277	2	28.013	0.117
Benzene, 1-methyl-2-nitro-	air, water, soil	137.138	1	14.007	0.102
Benzene, pentachloronitro-	air, water, soil	295.321	1	14.007	0.047
Benzidine	air, water, soil	184.242	2	28.013	0.152
Beta-cypermethrin isomer	air, water, soil	416.298	1	14.007	0.034
Bifenox	air, water, soil	342.128	1	14.007	0.041
Bitertanol	air, water, soil	337.423	3	42.020	0.125
Bromoxynil	air, water, soil	276.915	1	14.007	0.051
Bromuconazole	air, water, soil	377.063	3	42.020	0.111
Captan	air, water, soil	300.578	1	14.007	0.047
Carbaryl	air, water, soil	201.225	1	14.007	0.070
Carbendazim	air, water, soil	191.190	3	42.020	0.220
Carbetamide	air, water, soil	236.271	2	28.013	0.119
Carbofuran	air, water, soil	221.256	1	14.007	0.063
Carfentrazone-ethyl	air, water, soil	412.190	3	42.020	0.102
Cellulose, nitrate	air, water, soil	999.405	11	154.074	0.154
Chloramben, ammonium salt	air, water, soil	223.053	2	28.013	0.126
Chloramben, methyl ester	air, water, soil	220.049	1	14.007	0.064
Chloramine	air, water, soil	51.473	1	14.007	0.272

Substance/Compound	**Compartment**	**Molar mass [g/mol]**	**Nitrogen atoms**	**Nitrogen content [g/mol]**	**Nc - Nitrogen coefficient**
Chloramine-b	air, water, soil	213.611	1	14.007	0.066
Chloridazon	air, water, soil	221.644	3	42.020	0.190
Chlorimuron-ethyl	air, water, soil	414.817	4	56.027	0.135
Chlormequat	air, water, soil	122.616	1	14.007	0.114
Chlorothalonil	air, water, soil	265.902	2	28.013	0.105
Chlorpyrifos	air, water, soil	350.575	1	14.007	0.040
Chlorsulfuron	air, water, soil	357.769	5	70.034	0.196
Chlortoluron	air, water, soil	212.677	2	28.013	0.132
Choline chloride	air, water, soil	139.623	1	14.007	0.100
Cinidon-ethyl	soil	394.248	1	14.007	0.036
Clethodim	air, water, soil	359.909	1	14.007	0.039
Clodinafop-propargyl	air, water, soil	349.742	1	14.007	0.040
Clomazone	air, water, soil	239.699	1	14.007	0.058
Clopyralid	air, water, soil	191.995	1	14.007	0.073
Cloquintocet-mexyl	air, water, soil	335.828	1	14.007	0.042
Cloransulam-methyl	air, water, soil	429.807	5	70.034	0.163
Cyanide	air, water	26.018	1	14.007	0.538
Cyanoacetic acid	air	85.062	1	14.007	0.165
Cycloxydim	air, water, soil	325.467	1	14.007	0.043
Cyfluthrin	air, water, soil	434.288	1	14.007	0.032
Cyhalothrin	air, water, soil	449.854	1	14.007	0.031
Cyhalothrin, gamma-	air, water, soil	449.854	1	14.007	0.031
Cymoxanil	air, water, soil	198.182	4	56.027	0.283
Cypermethrin	air, water, soil	416.298	1	14.007	0.034
Cyproconazole	air, water, soil	291.779	3	42.020	0.144
Cyprodinil	air, water, soil	225.295	3	42.020	0.187
Deltamethrin	air, water, soil	505.206	1	14.007	0.028
Desmedipham	air, water, soil	300.314	2	28.013	0.093
Diazinon	air, water, soil	304.345	2	28.013	0.092
Dicrotophos	air, water, soil	237.192	1	14.007	0.059
Diethylamine	air, water, soil	73.139	1	14.007	0.192
Difenoconazole	air, water, soil	406.263	3	42.020	0.103
Diflubenzuron	air, water, soil	310.685	2	28.013	0.090
Diflufenican	air, water, soil	394.301	2	28.013	0.071
Diflufenzopyr-sodium	air, water, soil	356.265	4	56.027	0.157
Dimethachlor	air, water, soil	255.742	1	14.007	0.055
Dimethenamid	air, water, soil	275.791	1	14.007	0.051
Dimethoate	air, water, soil	229.249	1	14.007	0.061
Dimethomorph	air, water, soil	387.860	1	14.007	0.036
Dimethylamine	air, water, soil	45.085	1	14.007	0.311
Dinitrogen monoxide	air, water, soil	44.013	2	28.013	0.636
Dinitrosohomopiperazine	air, water, soil	158.161	4	56.027	0.354
Dipropylamine	air, water, soil	101.193	1	14.007	0.138
Diquat	air, water, soil	184.242	2	28.013	0.152
Diquat dibromide	air, water, soil	344.050	2	28.013	0.081
Dithianone	air, water, soil	296.318	2	28.013	0.095
Diuron	air, water, soil	233.092	2	28.013	0.120
Epoxiconazole	air, water, soil	329.759	3	42.020	0.127
Esfenvalerate	air, water, soil	419.905	1	14.007	0.033

Substance/Compound	**Compartment**	**Molar mass [g/mol]**	**Nitrogen atoms**	**Nitrogen content [g/mol]**	**Nc - Nitrogen coefficient**
Ethalfluralin	air, water, soil	333.267	3	42.020	0.126
Ethane, Z-ethyl-O,N,N-azoxy-	air, water, soil	102.137	2	28.013	0.274
Ethylamine	air, water, soil	45.085	1	14.007	0.311
Ethylene diamine	air, water, soil	60.100	2	28.013	0.466
Fenbuconazole	air, water, soil	336.823	4	56.027	0.166
Fenoxaprop	air, water, soil	333.724	1	14.007	0.042
Fenoxaprop-P ethyl ester	air, water, soil	361.778	1	14.007	0.039
Fenpiclonil	air, water, soil	237.083	2	28.013	0.118
Fenpropathrin	air, water, soil	349.430	1	14.007	0.040
Fenpropidin	air, water, soil	273.464	1	14.007	0.051
Fenpropimorph	air, water, soil	303.490	1	14.007	0.046
Fipronil	air, water, soil	437.141	4	56.027	0.128
Florasulam	soil	359.283	5	70.034	0.195
Fluazifop-P-butyl	air, water, soil	383.367	1	14.007	0.037
Flucarbazone sodium salt	soil	418.279	4	56.027	0.134
Fludioxonil	air, water, soil	248.189	2	28.013	0.113
Flufenacet	air, water, soil	363.331	3	42.020	0.116
Flumetsulam	air, water, soil	325.294	5	70.034	0.215
Flumiclorac-pentyl	air, water, soil	423.865	1	14.007	0.033
Flumioxazin	air, water, soil	354.337	2	28.013	0.079
Fluroxypyr	air, water, soil	255.026	2	28.013	0.110
Flurtamone	soil	333.310	1	14.007	0.042
Flusilazole	air, water, soil	315.399	3	42.020	0.133
Folpet	air, water, soil	296.546	1	14.007	0.047
Fomesafen	air, water, soil	438.758	2	28.013	0.064
Foramsulfuron	air, water, soil	452.442	6	84.040	0.186
Formamide	air, water, soil	45.041	1	14.007	0.311
Glyphosate	air, water, soil	169.073	1	14.007	0.083
Hydramethylnon	air, water, soil	494.485	4	56.027	0.113
Imazamox	air, water, soil	305.334	3	42.020	0.138
Imazapyr	air, water, soil	261.281	3	42.020	0.161
Imazaquin	air, water, soil	311.341	3	42.020	0.135
Imazethapyr	air, water, soil	289.335	3	42.020	0.145
Imidacloprid	air, water, soil	255.662	5	70.034	0.274
Indoxacarb	air, water, soil	527.837	3	42.020	0.080
Ioxynil	air, water, soil	370.916	1	14.007	0.038
Iprodione	air, water, soil	330.165	3	42.020	0.127
Isocyanic acid	air	43.025	1	14.007	0.326
Isopropylamine	air, water, soil	59.112	1	14.007	0.237
Isoproturon	air, water, soil	206.289	2	28.013	0.136
Isoxaflutole	air, water, soil	359.319	1	14.007	0.039
Kresoxim-methyl	air, water, soil	313.353	1	14.007	0.045
Lactofen	air, water, soil	461.774	1	14.007	0.030
Lambda-cyhalothrin	air, water, soil	449.854	1	14.007	0.031
Linuron	air, water, soil	249.091	2	28.013	0.112
Mancozeb	air, water, soil	541.010	4	56.027	0.104
Mefenpyr	soil	317.122	2	28.013	0.088
Mefenpyr-diethyl	soil	373.230	2	28.013	0.075
Mepiquat chloride	air, water, soil	149.662	1	14.007	0.094

Substance/Compound	Compartment	Molar mass [g/mol]	Nitrogen atoms	Nitrogen content [g/mol]	Nc - Nitrogen coefficient
Mesotrione	air, water, soil	339.318	1	14.007	0.041
Metamitron	air, water, soil	202.217	4	56.027	0.277
Metazachlor	air, water, soil	277.752	3	42.020	0.151
Methomyl	air, water, soil	162.207	2	28.013	0.173
Methylamine	air, water, soil	31.058	1	14.007	0.451
Metolachlor	air, water, soil	283.796	1	14.007	0.049
Metribuzin	air, water, soil	214.287	4	56.027	0.261
Monocrotophos	air, water, soil	223.165	1	14.007	0.063
Monoethanolamine	air, water, soil	61.084	1	14.007	0.229
N-Nitrosodiethylamine	air, water, soil	102.137	2	28.013	0.274
Napropamide	air, water, soil	271.360	1	14.007	0.052
Nitrate	air, water, soil	62.005	1	14.007	0.226
Nitric oxide	air	30.006	1	14.007	0.467
Nitrite	air, water	46.005	1	14.007	0.304
Nitrobenzene	air, water, soil	123.111	1	14.007	0.114
Nitrogen	air	14.007	1	14.007	0.000
Nitrogen	water, soil	14.007	1	14.007	1.000
Nitrogen	raw material	14.007	1	14.007	0.000
Nitrogen dioxide	air, water, soil	46.005	1	14.007	0.304
Nitrogen fluoride	air	71.002	1	14.007	0.197
Nitrogen oxides	air, water, soil	46.005	1	14.007	0.304
Nitrogen, organic bound	water	n.a.	n.a	n.a	0.160
Nitrogen, total	air, water, soil	14.007	1	14.007	1.000
Nitrosamine-methyl-phenylethyl-	air, water, soil	164.208	2	28.013	0.171
Nitrosoheptamethyleneimine	air, water, soil	142.202	2	28.013	0.197
Nitrosomethylethylamine, N-	air, water, soil	88.110	2	28.013	0.318
Orbencarb	air, water, soil	257.776	1	14.007	0.054
Paraquat dichloride	air, water, soil	257.158	2	28.013	0.109
Parathion	air, water, soil	291.258	1	14.007	0.048
Particulates, < 2.5 µm	air	n.a	n.a	n.a	0.081
Particulates, > 2.5 µm, and < 10 µm	air	n.a	n.a	n.a	0.028
Particulates, < 10 µm	air, water	n.a	n.a	n.a	0.054
Pendimethalin	air, water, soil	281.312	3	42.020	0.149
Phenmedipham	air, water, soil	300.314	2	28.013	0.093
Pronamide	air, water, soil	256.130	1	14.007	0.055
Propanil	air, water, soil	218.077	1	14.007	0.064
Propiconazole	air, water, soil	342.220	3	42.020	0.123
Propylamine	air, water, soil	59.112	1	14.007	0.237
Pyridate	air, water, soil	378.915	2	28.013	0.074
Simazine	air, water, soil	201.658	5	70.034	0.347
Sulfentrazone	air, water, soil	387.183	4	56.027	0.145
t-Butylamine	air, water, soil	73.139	1	14.007	0.192
Tebupirimphos	air, water, soil	318.372	2	28.013	0.088
Tebutam	soil	233.355	1	14.007	0.060
Terbuthylazin	air, water, soil	229.712	5	70.034	0.305
Tralkoxydim	air, water, soil	329.440	1	14.007	0.043
Trifloxystrobin	air, water, soil	408.377	2	28.013	0.069
Trifluralin	air, water, soil	335.283	3	42.020	0.125
Trimethylamine	air, water, soil	59.112	1	14.007	0.237

Substance/Compound	Compartment	Molar mass [g/mol]	Nitrogen atoms	Nitrogen content [g/mol]	Nc - Nitrogen coefficient
Urea	air, water, soil	60.056	2	28.013	0.466
Used air	air	n.a.	n.a.	n.a.	0.000
Yellow ob	air, water, soil	261.328	3	42.020	0.161
Zineb	air, water, soil	275.726	2	28.013	0.102
Ziram	air, water, soil	305.796	2	28.013	0.092

An iterative approach was applied to identify the nitrogen-containing substances and to calculate the nitrogen coefficients: the above results are to be considered partial, as referred to the substances detected in the various applications of this work. However, it is considered that the coverage is wide enough to ensure the reliability of results for the purposes and applications proposed, as the cutoff criteria applied (ng output referred to functional units of 1 kg or comparable) is sufficiently restrictive. It must also be underlined that the databases considered are very complete, with particular reference to the Ecoinvent 3.1 database that, for the considered product systems, provides inventories results comprising, on the average, more than 1400 records.

During the analysis, some difficulties emerged which required some assumptions in order to calculate the nitrogen coefficients; difficulties emerged and assumptions made are summarized below to better contextualize the validity of the results obtained:

- Some inconsistencies have been found in the nomenclature adopted by the various databases, in particular with regard to emissions referred to as nitrogen, nitrogen total, nitrogen oxides, ammonia and ammonia as N. The different names used were all taken into account, in some cases formulating hypotheses regarding the composition of the substance, specifically:
  - "nitrogen total", voice of the LCA Food DK database, was considered as "nitrogen" emission to water or soil with a nitrogen coefficient equal to 1;
  - "nitrogen oxides" emissions were considered as "nitrogen dioxide", estimated as the substance most likely present among the various forms of nitrogen oxides;
  - for the determination of nitrogen content in the "nitrogen organic bound" emissions the standard nitrogen-to-protein conversion factor of 6.25 was used;
  - "ammonia as N" emissions to water were considered equivalent to nitrogen emissions to water with a nitrogen coefficient equal to 1.
- The considered databases include different types of emissions particulate matter (Particulates, < 2.5 μm; Particulates, > 10 μm; Particulates, > 2.5 μm, and < 10 μm; Particulates, < 10 μm) which, as is known, may contain nitrogen compounds, in particular classified as ammonium ion (NH_4^+)

and nitrate ion (NO_3^-). To estimate the nitrogen content of particulate, reference was made to the results reported by Sillanpää *et al.* (2006) related to the chemical composition of particulate matter at six urban sites in Europe. Specifically the average of the reported values was calculated, obtaining the following results:

- 8,52 % for the average content of NO_3^- in $PM_{2.5}$ (Particulates, < 2.5 μm);
- 8,78 % for the average content of NO_3^- in $PM_{2.5\text{-}10}$ (Particulates, > 2.5 μm, and < 10 μm);
- 7.9 % for the average content of NH_4^+ in $PM_{2.5}$ (Particulates, < 2.5 μm);
- 1.04 % for the average content of NH_4^+ in $PM_{2.5\text{-}10}$ (Particulates, > 2.5 μm, and < 10 μm).

For the output named as "Particulates, < 10 μm", the nitrogen content was estimated as the average of the outputs "Particulates, < 2.5 μm" and "Particulates, > 2.5 μm, and < 10 μm". No estimates were made regarding the output "Particulates, > 10 μm" as no reliable studies were found in the literature: however, it is supposed a non-relevant nitrogen content that does not affect the validity of the results.

- As discussed in Chapter 1, quantification of the rate of denitrification and its relationship to reactive nitrogen creation is a complex issue about which the research has not given satisfactory results to date. The databases analyzed do not provide any indication in this regard and are furthermore difficult to interpret with regard to the outputs named as "Nitrogen" in the compartments "air", "water", "soil" and "raw material". In this regard, the following assumptions were made:
  - the flow "Nitrogen" in the compartment "air" was considered as a result of denitrification processes or, in any case, an emission molecular nitrogen (N_2): a coefficient of 0 was assigned to this flow, assuming that the molecular nitrogen flows out of the system were accounted as "nitrogen" to air in the databases (this is a hypothesis that should be thorough and verified with a specific study on databases that is outside the scope of this work). This consideration is however supported by the fact that the flows "Nitrogen" as such are not considered in the categories of impact relative to the nitrogen in the characterization methods used, as explained below. Finally, it must be emphasized that, in the applications carried out, the "nitrogen" to air flows detected are quite low and their contribution does not affect in a decisive way the results. As it regards the choice of the coefficient 0, as highlighted also by Pelletier and Leip (2014), denitrification, through a series of intermediate gaseous nitrogen oxide products, returns reactive nitrogen to its most thermodynamically stable form, nitrogen gas (N_2). Emissions of

N_2 must therefore be assigned a characterization factor of 0 in impact assessments which quantify contributions to perturbation of the nitrogen cycle.

- the flow “Nitrogen” in the compartment “water” was considered as an emission of various forms of nitrogen to water accounted as nitrogen: to this flow was assigned a nitrogen coefficient equal to 1;
- the flow “Nitrogen” in the compartment “soil” was considered as an emission of various forms of nitrogen to soil accounted as nitrogen: to this flow was assigned a nitrogen coefficient equal to 1;
- the flow “Nitrogen” in the compartment “raw material” was considered as an input to the product system, as all flows in the databases assigned to the compartment “raw material”: to this flow was assigned a nitrogen coefficient equal to 0 as it was considered as part of the input streams of nitrogen fixed to produce different input to the product system. As already mentioned at the beginning of the paragraph, and verified by mass balances carried out, the databases do not contain reliable data regarding the streams of nitrogen entering the product system. For this reason, this flow was not accounted in the analysis, being not even usable as a comparison value.

These topics deserve a specific in-depth study starting from the results of this work.

In order to make the analysis more efficient, an automated procedure was also predisposed, which, starting from the inventory results, identifies substances and compounds in output, associates the respective nitrogen coefficient previously calculated according to the 3.1 and automatically calculates the value of the reactive nitrogen indicator according to the 3.2.

The results of the application of this step of the methodology to the 12 product systems and of the validation conducted by comparing the results with literature data are presented in the next chapter devoted to the application of the methodology.

It must be emphasized once again that the output of this step of the methodology, that is the reactive nitrogen calculated for the product system, is already a useful result for a general assessment of the impact related to the nitrogen cycle. In this sense, the first result of this work is to propose a methodology, fully based on a LCA approach, to calculate, in a standardized way and using reliable databases, the amount of reactive nitrogen emitted by the product system: this first result is comparable to what is currently defined as nitrogen footprint.

3.2.4 Nitrogen impact assessment profile formulating

This step of the methodology is aimed at obtaining an impact assessment profile of the product system starting from the results of the nitrogen inventory, that is from the streams of nitrogen-containing substances flowing out of the system. These streams are the input for the characterization step which, in turn, only takes into account impact categories for which are defined characterization factors related to nitrogen-containing flows, as previously described in § 3.1.3.2. In detail, this step of the methodology includes the following activities:

- selection of impact categories, category indicators and characterization models;
- assignment of nitrogen inventory results to the selected impact categories (classification);
- calculation of category indicator results (characterization).

Regarding the selection of characterization models, for the purposes of this work, it was decided to use as a reference the "ILCD 2011 Midpoint +" characterization methodology proposed by JRC as a collection of characterization methods (EC-JRC, 2010b; EC-JRC, 2011). This choice, as above highlighted, is due to the authoritativeness of the source and its recognizability by the scientific community and LCA practitioners. The proposed methodology, however, is general and can be translated with reference to any characterization methodology presenting a scientific value. Impact categories and category indicators selected are reported in the Table 3.1 of § 3.1.3.2. The characterizations methods are described in detail in the Appendix A.

Once chosen the characterization methods for different categories of selected impact, nitrogen inventory results must be assigned to the impact categories: this activity consists in comparing the results of nitrogen inventory with the input streams considered by the different impact categories, exhaustively assigning the corresponding streams. This operation is done automatically when an appropriate software is used as a support tool: within this work has been used the SimaPro software in the version 8.3.0 released by Pré Consultants.

Given the characterization factors, that derive from the chosen methods, and completed the classification, the category indicator results are calculated for the selected impact categories, according to the following:

$$category\ indicator\ result\ (I_k) = \sum_{i=1}^{n} \sum_{j=1}^{m} s_{i,j,k} * cf_{i,j,k} \quad \left[\frac{category\ indicator\ unit}{functional\ unit}\right], \qquad (3.3)$$

where:

- *I_k is the indicator result for the k impact category;*
- *k is the identification index of the nitrogen-related impact category;*
- *$s_{i,j,k}$ is the amount of the i nitrogen-containing substance in the j compartment assigned to the k nitrogen-related impact category [emission unit/functional unit];*
- *$cf_{i,j,k}$ is the characterization factor for the i substance in the j compartment defined for the k nitrogen-related impact category [category indicator unit/emission unit]: $cf_{i,j,k}=0$ if the substance is not assigned to the k impact category after the classification;*
- *i is the identification index of the specific substance/compound;*
- *j is the identification index of the substance compartment of emission;*
- *n is the total number of nitrogen-containing substance and compound for the product system;*
- *m is the total number of the compartments of emission.*

The calculation of category indicator results involves therefore the conversion of inventory results to common units and the aggregation of the converted results within the same impact category. For the proposed application, the category indicators quantify the environmental impacts, caused by streams of the nitrogen-containing substances in output from the product system, calculated according to the characterization methods underlying the impact categories and expressed according to the relative units of measurement.

In the Table 3.6 are shown the value of the characterization factors used within the proposed methodology. Specifically, the factors are derived from the above presented “ILCD 2011 Midpoint +” characterization methodology (EC-JRC, 2012) with the exception of the characterization factors for the category “climate change” which are updated to the result presented in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker *et al.*, 2013), according to the method known as “IPCC 2013 GWP 100a”. In detail, in order to ensure the readability of the Table, the following cut-off criteria were applied to select records to be reported:

- for the category “Human toxicity cancer effect”, the nitrogen-containing substances are reported whose characterization factor value provides a contribution > 0.001% with respect to the sum of the values of all the characterization factors for the substances assigned to the category applying the characterization method;
- for the category “Human toxicity non-cancer effect”, the nitrogen-containing substances are reported whose characterization factor value provides a contribution > 0.05% with respect to the sum of the values of all the characterization factors for the substances assigned to the category applying the characterization method;
- for the category “Ecotoxcity fresh water” the nitrogen-containing substances are reported whose characterization factor value provides a contribution > 1% with respect to the sum of the values

of all the characterization factors for the substances assigned to the category applying the characterization method: for this category, furthermore, are reported the characterization factors of all the substance resulting from inventory analyzes carried out as part of the present work.

- for all other impact categories, are reported the characterization factors of all the nitrogen-containing substances assigned to the specific category applying the characterization method.

Table 3.6. *Characterization factors for nitrogen-containing substances assigned to the nitrogen-related impact categories as defined by the "ILCD 2011 Midpoint +" characterization methodology. Cut-off criteria were applied for the impact categories Ecotoxity fresh water, Human toxicity cancer effect and Human toxicity non cancer effect. Source: Stocker et al. (2013) for Climate change factors; EC-JRC (2012) for other categories factors.*

Impact category	**Substance/ Compound**	**Compartment**	**Unit of measure**	**Characterization factor**
Climate change	Dinitrogen monoxide	air	kg CO_2 eq./kg	265
Climate change	Nitrogen fluoride	air	kg CO_2 eq./kg	16100
Particulate matter	Ammonia	air	kg $PM_{2.5}$ eq./kg	0.0667
Particulate matter	Nitric oxide	air	kg $PM_{2.5}$ eq./kg	0.0111
Particulate matter	Nitrogen dioxide	air	kg $PM_{2.5}$ eq./kg	0.00722
Particulate matter	Nitrogen oxides	air	kg $PM_{2.5}$ eq./kg	0.00722
Particulate matter	Particulates, < 10 μm	air	kg $PM_{2.5}$ eq./kg	0.228
Particulate matter	Particulates, < 2.5 μm	air	kg $PM_{2.5}$ eq./kg	1
Photoch. ozone formation	Nitric oxide	air	kg NMVOC eq./kg	1
Photoch. ozone formation	Nitrogen dioxide	air	kg NMVOC eq./kg	1
Photoch. ozone formation	Nitrogen oxides	air	kg NMVOC eq./kg	1
Acidification	Ammonia	air	molc H^+ eq./kg	3.02
Acidification	Nitric oxide	air	molc H^+ eq./kg	1.13
Acidification	Nitrogen dioxide	air	molc H^+ eq./kg	0.74
Acidification	Nitrogen oxides	air	molc H^+ eq./kg	0.74
Eutrophication, terrestrial	Ammonia	air	mol N eq./kg	13.5
Eutrophication, terrestrial	Ammonium, ion	air	mol N eq./kg	12.7
Eutrophication, terrestrial	Nitrate	air	mol N eq./kg	3.16
Eutrophication, terrestrial	Nitric oxide	air	mol N eq./kg	6.53
Eutrophication, terrestrial	Nitrite	air	mol N eq./kg	4.26
Eutrophication, terrestrial	Nitrogen dioxide	air	mol N eq./kg	4.26
Eutrophication, terrestrial	Nitrogen oxides	air	mol N eq./kg	4.26
Eutrophication, marine	Ammonia	air	kg N eq./kg	0.092
Eutrophication, marine	Ammonia	water	kg N eq./kg	0.824
Eutrophication, marine	Ammonium, ion	air	kg N eq./kg	0.087
Eutrophication, marine	Ammonium, ion	water	kg N eq./kg	0.778
Eutrophication, marine	Nitrate	air	kg N eq./kg	0.028
Eutrophication, marine	Nitrate	water	kg N eq./kg	0.226
Eutrophication, marine	Nitric oxide	air	kg N eq./kg	0.596
Eutrophication, marine	Nitrite	water	kg N eq./kg	0.304
Eutrophication, marine	Nitrogen dioxide	air	kg N eq./kg	0.389
Eutrophication, marine	Nitrogen oxides	air	kg N eq./kg	0.389
Eutrophication, marine	Nitrogen, total	water	kg N eq./kg	1
Ecotoxcity fresh water	Alachlor	soil	CTU_e/kg	9280
Ecotoxcity fresh water	Aldicarb	soil	CTU_e/kg	11900
Ecotoxcity fresh water	Antimycin A	water	CTU_e/kg	68800000
Ecotoxcity fresh water	Atrazine	soil	CTU_e/kg	11400
Ecotoxcity fresh water	Beta-cyperm. isomer	water	CTU_e/kg	166000000

Impact category	Substance/ Compound	Compartment	Unit of measure	Characterization factor
Ecotoxcity fresh water	Carbofuran	soil	CTU_e/kg	21600
Ecotoxcity fresh water	Chlorothalonil	soil	CTU_e/kg	57800
Ecotoxcity fresh water	Chlorpyrifos	soil	CTU_e/kg	106000
Ecotoxcity fresh water	Cyfluthrin	water	CTU_e/kg	490000000
Ecotoxcity fresh water	Cypermethrin	water	CTU_e/kg	50400000
Ecotoxcity fresh water	Diflubenzuron	soil	CTU_e/kg	170000
Ecotoxcity fresh water	Fenpropathrin	water	CTU_e/kg	114000000
Ecotoxcity fresh water	Fipronil	soil	CTU_e/kg	32300
Ecotoxcity fresh water	Folpet	soil	CTU_e/kg	381000
Ecotoxcity fresh water	Isoproturon	soil	CTU_e/kg	9460
Ecotoxcity fresh water	Lambda-cyhalothrin	water	CTU_e/kg	139000000
Ecotoxcity fresh water	Metolachlor	soil	CTU_e/kg	5960
Ecotoxcity fresh water	Parathion	soil	CTU_e/kg	83100
Ecotoxcity fresh water	Pendimethalin	soil	CTU_e/kg	2930
Ecotoxcity fresh water	Propanil	soil	CTU_e/kg	60400
Ecotoxcity fresh water	Terbuthylazin	soil	CTU_e/kg	53600
Human tox., canc. eff.	Diazepine, hexah. din	water	CTU_h/kg	0.00208
Human tox., canc. eff.	Benzidine	air	CTU_h/kg	0.00144
Human tox., canc. eff.	Benzidine	water	CTU_h/kg	0.00996
Human tox., canc. eff.	Azoxyethane	air	CTU_h/kg	0.00149
Human tox., canc. eff.	Azoxyethane	water	CTU_h/kg	0.00211
Human tox., canc. eff.	N-Nitrosodiethylam.	water	CTU_h/kg	0.00241
Human tox., canc. eff.	Met-phen-nitrosam.	air	CTU_h/kg	0.00266
Human tox., canc. eff.	Met-phen-nitrosam.	water	CTU_h/kg	0.00913
Human tox., canc. eff.	Nitrosoeptmeth.	water	CTU_h/kg	0.0023
Human tox., canc. eff.	N-nitrosomethy	water	CTU_h/kg	0.00168
Human tox., non-canc. eff.	Hydramethylnon	water	CTU_h/kg	0.0218

From the analysis of the characterization models included in the “ILCD 2011 Midpoint +” methodology, it emerged that certain impact categories are exclusively oriented to the assessment of impacts related to the nitrogen cycle, as they provide for characterization factors only in relation to nitrogen-containing substances: this is the case for example of categories terrestrial eutrophication and marine eutrophication. Other categories are strongly influenced by nitrogen-containing substances, such as acidification, which only considers nitrogen compounds and sulfur containing substances, or particulate matter. For other categories instead, nitrogen-containing substances have a lower weight, as in the case of climate change and photochemical ozone formation, or very poor, as in the case of toxicity related categories. In particular, the category freshwater ecotoxicity includes the emissions of various nitrogen-containing substances used in agriculture such as insecticides, herbicides or pesticides.

The calculation of the indicator result, as in 3.3, shall be performed for all the selected nitrogen-related impact categories, thus obtaining a set of z values where z is the number of the selected impact categories: as highlighted above, referring to the ILCD impact categories of JRC, for the proposed methodology the set consists of nine impact categories (z=9).

The union of the category indicator results for the selected impact categories, each with its own specific unit of measurement, constitutes the nitrogen impact assessment profile, as follows:

$$nitrogen\ impact\ assessment\ profile\ =\ \bigcup_{k=1}^{z} I_k \quad , \tag{3.4}$$

where:

- *I_k is the indicator result for the k impact category as defined in 3.3;*
- *k is the identification index of the nitrogen-related impact category;*
- *z is the number of the selected impact categories (for the application presented in this work z=9 as illustrated in § 3.1.2.2).*

According to the proposed methodology, the nitrogen impact assessment profile is potentially constituted by the union of nine results of category indicators, that is the indicators of the nine nitrogen-related impact categories. However, it may happen that, after the classification, no nitrogen-containing substances are associated with a specific impact category: in this case, the profile consists of fewer indicators: this circumstance can also occur as a result of the application of cut-off criteria, as shown below in the presented examples of application.

The nitrogen impact assessment profile, as it is defined, can not be represented in a single graph, each indicator result being expressed in its own unit of measure: it must therefore be reported in tabular form.

By way of example are reported in Table 3.7 the results of the calculation of the nitrogen impact assessment profile for a reference product system, specifically created for the purposes of this work, consisting of the union of ten categories (vegetables, cereals, vegetable-oils, fruit, dairy, fish, meat textiles, metals, and fuels) each comprising four products: more details about this product system are given in the next chapter devoted to the application of the methodology. For the calculation, a cut-off criterion of 0.1% was applied for determining the substances to account for the impact categories freshwater ecotoxicity, human toxicity cancer effect and human toxicity non-cancer effect: nitrogen-containing substances with a contribution less than 0.1% in terms of impact for each of these categories were excluded.

Table 3.7. *Example of nitrogen impact assessment profile calculated for a reference product system comprising 40 products assigned to 10 products categories. Cut-off criterion of 0.1% applied for the categories Freshwater ecotoxicity, Human toxicity cancer effect and Human toxicity non cancer effect.*

Impact category	Subtance	Compartm.	Unit	Category result
Climate change	Dinitrogen monoxide	Air	kg CO2 eq	3.11E+01
Climate change	Nitrogen fluoride	Air	kg CO2 eq	2.11E-06
Climate change	**Total**		**kg CO2 eq**	**3.11E+01**
Particulate matter	Ammonia	Air	kg PM2.5 eq	2.20E-02
Particulate matter	Nitrogen oxides	Air	kg PM2.5 eq	3.09E-03
Particulate matter	Particulates, < 10 µm (mobile)	Air	kg PM2.5 eq	1.21E-04
Particulate matter	Particulates, < 10 µm (stationary)	Air	kg PM2.5 eq	2.06E-04
Particulate matter	Particulates, < 2.5 µm	Air	kg PM2.5 eq	8.82E-02
Particulate matter	**Total**		**kg PM2.5 eq**	**1.14E-01**
Photoch. ozone formation	Nitrogen oxides	Air	kg NMVOC eq	4.20E-01
Photoch. ozone formation	**Total**		**kg NMVOC eq**	**4.20E-01**
Acidification	Ammonia	Air	molc H+ eq	9.96E-01
Acidification	Nitrogen oxides	Air	molc H+ eq	3.11E-01
Acidification	**Total**		**molc H+ eq**	**1.31E+00**
Terrestrial eutrophication	Ammonia	Air	molc N eq	4.45E+00
Terrestrial eutrophication	Nitrate	Air	molc N eq	1.41E-05
Terrestrial eutrophication	Nitrogen oxides	Air	molc N eq	1.79E+00
Terrestrial eutrophication	**Total**		**molc N eq**	**6.24E+00**
Marine eutrophication	Ammonia	Air	kg N eq	3.03E-02
Marine eutrophication	Ammonium, ion	Water	kg N eq	3.99E-03
Marine eutrophication	Nitrate	Air	kg N eq	1.25E-07
Marine eutrophication	Nitrate	Water	kg N eq	9.81E-01
Marine eutrophication	Nitrite	Water	kg N eq	5.65E-05
Marine eutrophication	Nitrogen oxides	Air	kg N eq	1.63E-01
Marine eutrophication	Nitrogen, total	Water	kg N eq	2.09E-03
Marine eutrophication	**Total**		**kg N eq**	**1.18E+00**
Freshwater ecotoxicity	Aldicarb	Soil	CTUe	5.84E+00
Freshwater ecotoxicity	Chlorpyrifos	Soil	CTUe	4.24E+01
Freshwater ecotoxicity	Diflubenzuron	Soil	CTUe	2.46E+01
Freshwater ecotoxicity	Fipronil	Soil	CTUe	5.14E+00
Freshwater ecotoxicity	Folpet	Soil	CTUe	7.00E+00
Freshwater ecotoxicity	Parathion	Soil	CTUe	7.16E+00
Freshwater ecotoxicity	Propanil	Soil	CTUe	1.68E+01
Freshwater ecotoxicity	**Total**		**CTUe**	**1.09E+02**
Human tox., cancer eff.	**Total**		**CTUh**	**0.00E+00**
Human tox., non-cancer eff.	**Total**		**CTUh**	**0.00E+00**

The results obtained after the characterization phase of the proposed methodology, that is the nitrogen impact assessment profile, are considered the most reliable, scientifically, within the impact assessment process. The environmental mechanisms underlying the characterization models proposed in this work, in fact, find the consent of the scientific community and are widely used in the LCA applications. The presented midpoint characterization factors are currently the most recognized way, from a scientific point of view, to quantify the link between substance and energy flows of a product system and the caused environmental impact.

It should be emphasized that the impact profile accounts potential environmental impacts caused by the analyzed product system with regard to the nitrogen cycle, providing information on the nature of the changes caused to the environment and on their scale. In this sense, the information provided is much more complete than that contained in an aggregate indicator, such as reactive nitrogen indicator previously seen, which only presents general indications of the potential overall impact of the analyzed system.

It is also worth noting that all the subsequent operations carried out starting from impact assessment profile results, such as normalization and weighting below presented, while making the results more understandable and usable, introduce degrees of subjectivity to the analysis, thus decreasing the scientific value of the results.

As previously illustrated in the Figure 3.4, the characterization, or “calculation of impact category indicator results”, is identified by the ISO standards as the last mandatory element of the life cycle impact assessment.

3.2.5 Single score nitrogen impact indicator calculating

This section describes the final step provided for the impact assessment by the proposed methodology, subsequent to the characterization step. Specifically, in two different subsections for ease of reading, the operation of the normalization and weighing are presented: the aim of this final step, as a whole, is to calculate a result for the assessment of the impact related to the nitrogen cycle, expressed as a single score indicator.

3.2.5.1 Normalization

As seen above, the result of the characterization step consists of a nitrogen impact assessment profile, that is the union of the results of different category indicators, each expressed in its own unit of measure. A subsequent operation, aimed at providing and communicating information on the relative significance of the indicator results, and preparing for additional procedures, such as grouping and weighting is the normalization. It consists in the calculation of the magnitude of the category indicator results relative to some reference information. The aim is to put in evidence, to better understand, the relative magnitude for each indicator result of the product system under study.

Starting from the indicator results for the selected impact categories and applying the normalization factors presented in §3.1.3.3, the corresponding normalized indicator results are calculated as follows:

$$normalized\ indicator\ result\ (norm\ I_k)\ =\ \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} s_{i,j,k} * cf_{i,j,k}}{nf_k}\quad \left[\frac{equivalent\ persons}{functional\ unit}\right], \qquad (3.5)$$

where:

- *norm I_k is the normalized indicator result for the k impact category;*
- *k is the identification index of the nitrogen-related impact category;*
- *$s_{i,j,k}$ is the amount of the i nitrogen-containing substance in the j compartment assigned to the k nitrogen-related impact category [emission unit/functional unit];*
- *$cf_{i,j,k}$ is the characterization factor for the i substance in the j compartment defined for the k nitrogen-related impact category [category indicator unit/emission unit];*
- *nf_k is the normalization factor defined for the k impact category: for this study the JRC normalization factors per person are used;*
- *i is the identification index of the specific substance/compound;*
- *j is the identification index of the compartment of emission of the nitrogen-containing substance;*
- *n is the total number of nitrogen-containing substance and compound for the product system;*
- *m is the total number of the compartments of emission (for this study m=3; the considered compartments are: air, water, soil).*

Considering that the normalization factors recommended by JRC (Benini *et al.*, 2014) used within this work are expressed as unit of measure of impact categories per person, the indicator results, after the normalization are expressed as “equivalent persons” related to the functional unit defined for the product system. After the normalization, the indicator results represent the magnitude of the impacts compared to the estimated reference impact per person and are therefore all expressed in a common unit of measure.

Similarly to what seen in the 3.4 regarding the impact profile, the normalized nitrogen impact assessment profile can therefore be expressed as follows:

$$normalized\ nitrogen\ impact\ assessment\ profile\ =\ \bigcup_{k=1}^{z}\ norm\ I_k\quad , \qquad (3.6)$$

where:

- *norm I_k is the normalized indicator result for the k impact category calculated as in 3.5;*
- *k is the identification index of the nitrogen-related impact category;*
- *z is the number of the nitrogen related selected impact categories.*

The normalized impact assessment profile can easily be reported as a result in a single graph, being the indicator results expressed by a common unit of measure. By way of example are reported in the Figure 3.7 the results of the normalization of the reference product system impact assessment profile whose results are reported in the previous paragraph (Table 3.7).

The same cut-off criteria as described above have been used to account the contribution of the substances to the impact categories. For easier reading, furthermore, the impact categories Human toxicity cancer effect and Human toxicity non-cancer effect, to which a null value was assigned after the characterization, are not reported in the graph.

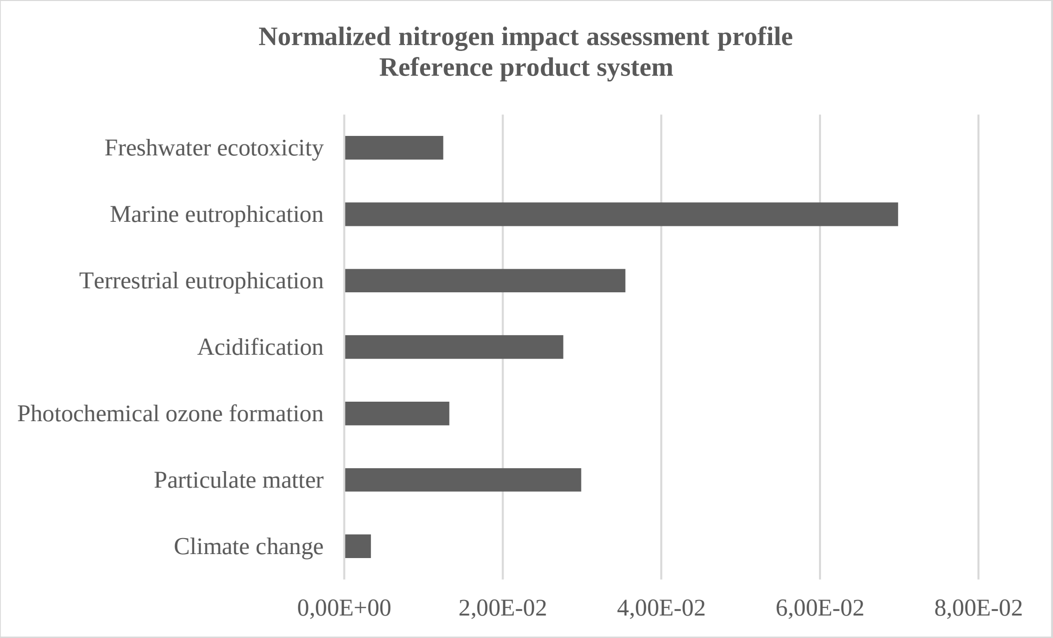


Figure 3.7. *Example of results of normalized impact assessment profile calculated for a reference product system comprising 40 products assigned to 10 products categories. Null results not reported for categories, Human toxicity cancer effect and Human toxicity non cancer effect.*

Compared to the results of nitrogen impact assessment profile, reported in the Table 3.7, the normalized results allow a greater comprehensibility and a direct comparison between the impact categories results, as the indicator results are expressed in the same unit of measure. The normalization operation, however, introduces a greater degree of subjectivity in the assessment, since the account of normalization factors involves methodological and calculation choices that, although largely accepted and used, deviate the results from the scientific nature that belongs to the characterization results.

As a further example, are reported in the Figure 3.8 the results of the normalization of the impact assessment profile concerning the comparison between two production alternatives (organic and conventional) for obtaining 1 kg of barley. More details about the product systems of this example are given in the next chapter devoted to the application of the methodology.

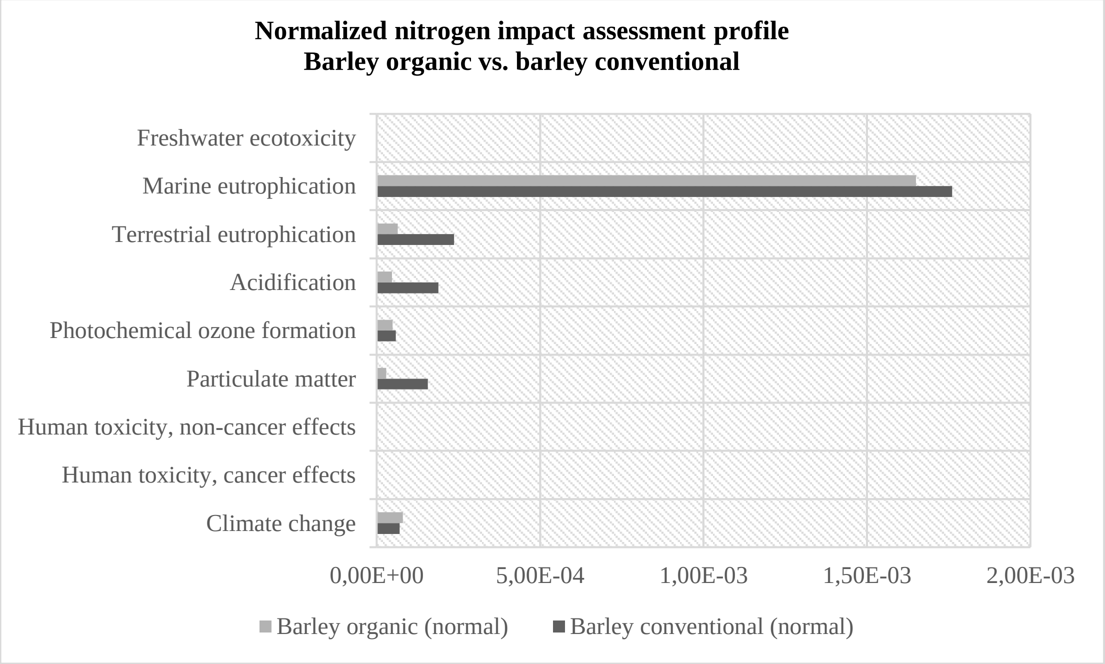


Figure 3.8. *Example of results of normalized impact assessment profile concerning the comparison of two production alternatives. The functional units for the analyzed product systems consist of the production of 1 kg of barley through organic and conventional farming.*

With regard to the above results, applying a cut off criterion of 0.01% in terms of impact for the categories Freshwater ecotoxicity, Human toxicity cancer effect and Human toxicity non cancer effect, the contribution of the nitrogen-containing substances is null for the categories Human toxicity cancer effect and Human toxicity non cancer effect, while is very low for the category Freshwater ecotoxicity (for this last category, the normalized results are equal to 1,35E-06 for conventional barley and to 9,60E-11 for organic barley, therefore are not visible in the graph).

As can be seen, in the case of the evaluation of different alternatives, the normalized result chart allows for an immediate feedback to make a first comparative assessment. In the above case, it is clear that the "organic production" alternative present a lesser environmental impact, referred to the nitrogen cycle, for all impact categories, with exception of the category climate change.

Finally, as for the characterization methods, it is emphasized that the proposed methodology is general and can be applied with reference to any normalization scheme presenting a scientific value, regardless of the normalization factors chosen.

3.2.5.2 Weighting and single score indicator calculating

Once obtained the normalized result of the nitrogen impact assessment profile, it may be appropriate to assess the relative importance of impact categories through a weighting operation. According to the ISO requirements for LCA (ISO, 2006b), weighting is the process of converting indicator results of different impact categories by using numerical factors based on value-choices. As defined, weighing is an operation that introduces further elements of subjectivity with respect to what already seen regarding the normalization. In fact, as once again underlined by ISO (2006b) "different individuals, organizations and societies may have different preferences; therefore it is possible that different parties will reach different weighting results based on the same indicator results or normalized indicator results. In an LCA it may be desirable to use several different weighting factors and weighting methods and to conduct sensitivity analysis to assess the consequences on the LCIA results of different value-choices and weighting methods".

Within the proposed methodology, a specific internal weighting method has been designed, based on data directly derived from the analyzed system. The basic idea was to calculate weighing factors that were proportional to the amount of reactive nitrogen referable to each specific impact category: applying these factors, a greater weight is given to the impact categories to which are assigned the nitrogen-containing substances causing higher emissions in terms of reactive nitrogen. The method to calculate the weighting factors starts from the reactive nitrogen accounting for each considered impact category, also summing the contributions of the different product systems in the case of a comparative analysis, according to the following:

$$category\ reactive\ nitrogen\ (CNr_k) = \sum_{x=1}^{p} \sum_{i=1}^{w} \sum_{j=1}^{m} s_{i,j,x,k} * Nc_{i,j} \left[\frac{mass\ unit\ of\ measure}{functional\ unit}\right], \quad (3.7)$$

where:

- *CNr_k is the reactive nitrogen calculated for the k impact category;*
- *$s_{i,j,x,k}$ is the amount of the i nitrogen-containing substance in the j compartment accounted for the x product system and assigned to the k nitrogen-related impact category [emission unit/functional unit];*
- *$Nc_{i,j}$ is the nitrogen coefficient for the i substance in the j compartment, calculated as in 3.1;*

- *i is the identification index of the specific substance/compound;*
- *j is the identification index of the compartment of emission of the nitrogen-containing substance;*
- *x is the identification index of the analyzed system;*
- *k is the identification index of the nitrogen-related impact category;*
- *p is the total number of analyzed product systems: p=1 for single product system analysis, p>1 for comparative analysis of different product systems;*
- *w is the number of nitrogen-containing substance assigned to the k impact category after the classification (with $w \leq n$, where n is the total number of nitrogen-containing substance for the whole product system);*
- *m is the total number of the compartments of emission (for this study m=3; the considered compartments are: air, water, soil).*

Considering that the number of nitrogen-containing substance assigned to an impact category is ≤ of the number of nitrogen-containing substance of the product system, the following applies to each product system:

$$CNr_k \leq N_r \quad , \tag{3.1}$$

where:

- *$C\,Nr_k$ is the reactive nitrogen calculated for the k impact category as in 3.7;*
- *k is the identification index of the nitrogen-related impact category;*
- *N_r is the total reactive nitrogen calculated for the product system as in 3.2.*

Once calculated the category reactive nitrogen for each impact category and for each product system (in case of analysis of different product systems), the weighting factor for each impact category is calculated as follows:

$$category\ weighting\ factor\ (wf_k\,) = \frac{C\ Nr_k}{\sum_{k=1}^{z} C\ Nr_k} \quad , \tag{3.9}$$

where:

- *wf_k is the weighting factor calculated for the k impact category;*
- *$C\,Nr_k$ is the reactive nitrogen calculated for the k impact category as in 3.5;*
- *k is the identification index of the nitrogen-related impact category;*
- *z is the number of the selected impact categories (for the application presented in this work z=9).*

By combining the equations 3.7 and 3.9, the following formula for the direct calculation of the category weighting factor is obtained:

$$category\ weighting\ factor\ (wf_k) = \frac{\sum_{x=1}^{p}\sum_{i=1}^{w}\sum_{j=1}^{m} s_{i,j,x,k}{*}Nc_{i,j}}{\sum_{k=1}^{z}\sum_{x=1}^{p}\sum_{i=1}^{w}\sum_{j=1}^{m} s_{i,j,x,k}{*}Nc_{i,j}} \quad , \qquad (3.10)$$

where

- wf_k *is the weighting factor calculated for the k impact category;*
- $s_{i,j,x,k}$ *is the amount of the i nitrogen-containing substance in the j compartment accounted for the x product system and assigned to the k nitrogen-related impact category [emission unit/functional unit];*
- $Nc_{i,j}$ *is the nitrogen coefficient for the i substance in the j compartment, calculated as in 3.1;*
- *i is the identification index of the specific substance/compound;*
- *j is the identification index of the compartment of emission of the nitrogen-containing substance;*
- *x is the identification index of the analyzed system;*
- *k is the identification index of the nitrogen-related impact category;*
- *z is the number of the selected impact categories;*
- *p is the total number of analyzed product systems: p=1 for single product system analysis, p>1 for comparative analysis of different product systems;*
- *w is the number of nitrogen-containing substance assigned to the k impact category after the classification (with* $w \leq n$*, where n is the total number of nitrogen-containing substance for the whole product system);*
- *m is the total number of the compartments of emission (for this study m=3; the considered compartments are: air, water, soil).*

The above presented weighting method has some peculiar features that is considered appropriate to highlight below:

- The method has a lower degree of subjectivity than weighing methods based on value-choices or panel weighting methods. Weighing factor are indeed specifically calculated for the product systems analyzed starting from internal data of the inventory analysis and characterization results, therefore not by resorting to external data and information that inevitably introduce elements of subjectivity to the analysis.
- The values of the weighting factors are not defined as one-time, but must be calculated from time to time based on the specific application and are variable in function of the analyzed product systems.
- The method tends to amplify the magnitude of the impact categories to which the most significant emissions of nitrogen-containing substances are assigned after the classification, thereby diminishing the importance of the categories less related to the nitrogen impacts and “flattening” the other results: this topic is best tackled also in the following discussion.
- The method is expensive respect to the calculation procedure, especially if considered in relation to standard methods that provide predefined values for the weighting factors.

- The method does not take into account value-choices, which in some cases may be useful to include as elements for the assessment.

Within the present work, an additional weighting system was also calculated using the above presented method applied to a reference product system specifically created for the purposes of this analysis. In detail, as already mentioned, the reference product system consists of the union of ten categories (vegetables, cereals, vegetable-oils, fruit, dairy, fish, meat textiles, metals, and fuels) each comprising four products, each considered with a functional unit equal to 1 kg: more details about this product system are given in the next chapter devoted to the application of the methodology.

In the second column of Table 3.8 are reported the values of the waiting factor for the nitrogen- related impact categories calculated by applying the presented weighting method to the reference product system: they are compared with the weighting set (reported in the third column) calculated starting from the proposal of Huppes and van Oers (2011) as previously presented in § 3.1.3.3.

Table 3.8. *Weighting sets [%] comparison: second column: calculated with the proposed method applied to the reference product system; third column: calculated starting from the proposal of Huppes and van Oers (2011).*

	Weighting set [%]	
ILCD recommended midpoint impact categories	**Weighting factors calculated by the proposed method applied to a reference product system**	**Weighting factors derived form Hupper and van Oers proposal**
Climate change	2.675	35.6
Acidification	14.290	6.2
Eutrophication, terrestrial	14.290	3.6
Eutrophication, marine	49.608	3.6
Photochemical ozone formation	4.578	7.7
Human toxicity – cancer effects	0.005	9.3
Human toxicity - non-cancer effects	0.005	6.2
Particulate matter / Respiratory inorganics	14.544	10.8
Ecotoxicity	0.010	17.0
Total	**100**	**100**

As can be noted, also the application of the proposed weighting methods to the reference product system, gives as a result weighting factors rather high for the impact categories to which the major emissions of nitrogen-containing substances are linked (such as for example marine eutrophication, acidification, terrestrial eutrophication and particulate matter). On the contrary, the calculated factors are very low for the other impact categories less affected by nitrogen-containing substances emissions (in particular for human toxicity – cancer and non-cancer effects and ecotoxicity): this could lead to excessive imbalance in the results compared to weighting methods based on expert panel. On the other hand, however, given that the scope of assessment is limited to the impacts linked to the nitrogen cycle, it is deemed consistent to assign lesser importance, in the weighting process, to the impact categories that have little relevance for the nitrogen cycle. From the application of the methodology to different product systems, moreover, it was found that the impact categories to which the method attributes less weight are just human toxicity (cancer and non-cancer effects) and ecotoxicity for which, as noted above, there is less scientific agreement both with regard to the characterization methods and with regard to the normalization factors. It is also worth noting the high weighting factor attributed to the climate change category from the panel method, which it is very sensitive to the current opinions and media communication on environmental impacts.

Other weighting factors derived by panel weighting methods were anyway presented in the § 3.1.3.3. Regardless of the method used, once calculated or obtained the weighting factors, starting from the normalized indicator result, and similarly to what expressed in the 3.5, the weighted nitrogen indicator result can be calculated for each selected impact category as follows:

$$weighted\ indicator\ result\ (wt\ I_k) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} s_{i,j,k} * cf_{i,j,k}}{nf_k} * \ wf_k \quad , \tag{3.11}$$

where:

- *wt I$_k$ is the weighted (after normalization) indicator result for the k impact category;*
- *wf$_k$ is the weighting factor calculated for the k impact category as in 3.10;*
- *other parameters and indices are defined with the same meaning and used in the same way as in the previous equations.*

Analogously to what expressed in the previous 3.4 and 3.6, the weighted nitrogen impact assessment profile consists of the union of the weighted indicator results calculated for each select impact category, according to the following:

$$weighted\ nitrogen\ impact\ assessment\ profile\ = \bigcup_{k=1}^{z}\ wt\ I_k \quad , \tag{3.12}$$

where:

- *wt I$_k$ is the weighted indicator result for the k impact category defined as in 3.11;*
- *other parameters and indices are defined with the same meaning and used in the same way as in the previous equations.*

By way of example, is reported in the Figure 3.9 the impact assessment profile calculated after the weighting process concerning the comparison between two production alternatives (organic and conventional) for obtaining 1 kg of barley: the analyzed product systems are the same as in the previous paragraph as example for the normalization process. For this application, the weighting factor calculation method presented as part of the proposed methodology was used, obtaining the weighting factors listed below for each impact category:

- climate change: 4.50%;
- human toxicity, cancer effects: 0 %
- human toxicity, non-cancer effects: 0%
- particulate matter: 4.62%;
- photochemical ozone formation: 1.40%;
- acidification: 4.58%;
- terrestrial eutrophication: 4.58%;
- marine eutrophication: 80.32%;
- freshwater ecotoxicity: 0.00012%.

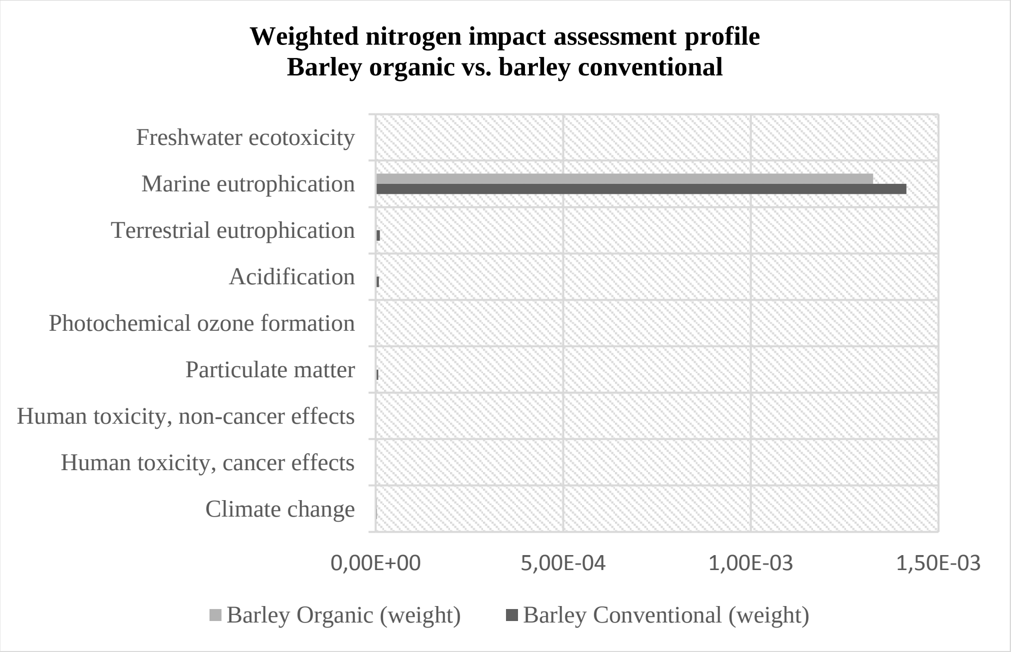


Figure 3.9. *Example of results of weighted impact assessment profile concerning the comparison of two production alternatives. The functional units for the analyzed product systems consist of the production of 1 kg of barley through organic and conventional farming.*

As for the comparison of alternatives, the results obviously reflect those obtained after normalization, the “organic production” alternative presenting a lesser environmental impact for all impact categories, with exception of the category climate change.
Similarly to what has been said about normalization, the weighting process introduces a further degree of subjectivity in the assessment, compared to the results of the nitrogen impact profile obtained after the characterization step. In this case, the methodological and calculation choices related to the weighting factors, are reflected in particular in the relative importance attributed to the impact categories: the degree of subjectivity increases in particular when the weighting set is selected on the basis of value-choices or panel weighting methods.

Finally, the single score nitrogen impact indicator for the analyzed product system can be defined as follows:

$$single\ score\ nitrogen\ impact\ indicator = \sum_{k=1}^{z} wt\ I_k \quad , \tag{3.13}$$

where:

- *wt I_k is the weighted indicator result for the k impact category defined as in 3.11;*
- *k is the identification index of the nitrogen-related impact category;*
- *z is the number of the selected impact categories.*

By combining the previous equations, the following formula is obtained which synthesizes the calculation of the single score nitrogen impact indicator:

$$single\ score\ N\ impact\ indicator = \sum_{k=1}^{z} \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} s_{i,j,k} * cf_{i,j,k}}{nf_k} * \frac{\sum_{x=1}^{p}\sum_{i=1}^{w}\sum_{j=1}^{m} s_{i,j,x,k} * Nc_{i,j}}{\sum_{k=1}^{z}\sum_{x=1}^{p}\sum_{i=1}^{w}\sum_{j=1}^{m} s_{i,j,x,k} * Nc_{i,j}}, \tag{3.14}$$

where:

- *all the parameters and indices are defined with the same meaning and used in the same way as in the previous equations.*

This indicator represents an assessment of environmental impacts of a product system related to the nitrogen cycle, expressed as a single stand-alone indicator.

For completeness, in the Figure 3.10 are reported the results of the calculation of the nitrogen impact indicator concerning the comparison between the two cultivation alternatives for barley production also used in the previous examples.

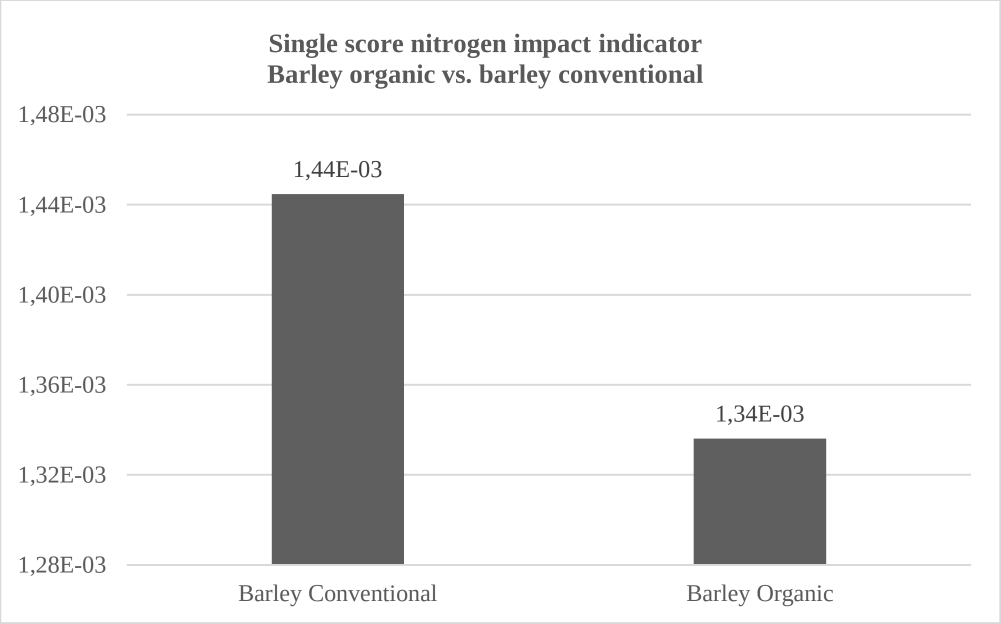


Figure 3.10. *Example of results of nitrogen impact indicator concerning the comparison of two production alternatives. The functional units for the analyzed product systems consist of the production of 1 kg of barley through organic and conventional farming.*

As can be seen, the summation of the weighted indicator results for the impact categories gives as a result a single value representative of the impact of the product system in relation to the nitrogen cycle. In the case of comparison between different systems, the single result also resolves any inconsistencies that emerge after the step of characterization, in the case where the alternatives have different ranking depending on the impact categories considered. In the above reported comparative application, for instance, the alternatives were differently ranked for the climate change category than the other impact categories.

3.2.6 Interpretation of the results

The final phase of the proposed methodology, ***interpretation of the results,*** is aimed at consider the findings from all the operative steps (inventory, and assessment) to deliver results that are consistent with the defined goal and scope and at reach conclusions, explain limitations and provide recommendations.

It is not provided, within the methodology, a standard procedure to conduct the interpretation of results, however, referring once again to ISO standards (ISO, 2006b) and to JRC publications on LCA (EC-JRC, 2010a) can be proposed a scheme with the elements to be considered in the interpretation phase, and their relation to the other phases and steps of the methodology.

In particular, as also reported by Zampori *et al.* (2016), the elements to be considered in the interpretation phase can be grouped in:

- Identification of significant issues (based on the results of the inventory and assessment phases). The purpose of this element of interpretation is to analyze and structure the results of earlier phases of the methodology in order to identify the significant issues. There are two interrelated aspects of significant issues: i) firstly there are the main contributors to the impact assessment results, i.e. most relevant life cycle stages, processes and elementary flows, and most relevant impact categories; ii) secondly, there are the main choices that have the potential to influence the precision of the final results of the application. These can be methodological choices, assumptions, foreground and background data used for deriving the process inventories, characterization methods used, as well as the used normalization and weighting factors.
- Evaluation that considers completeness, sensitivity and consistency checks. Completeness checks on the inventory are performed in order to determine the degree to which it is complete and whether the cut-off criteria have been met. Sensitivity checks have the purpose to assess the reliability of the final results and of the conclusions and recommendations derived from the application. The consistency check is performed to investigate whether the assumptions, methods and data have been applied consistently throughout the application.
- Conclusions, limitations and recommendations. Integrating the outcome of the other elements of the interpretation phase, and drawing on the main findings from the earlier phases of the methodology, the final element of the interpretation is to draw conclusions and identify limitations of the application, and to develop recommendations for the intended audience in accordance with the goal definition and the intended applications of the results.

Chapter 4

Assessment of impact related to nitrogen cycle: methodology application

This chapter presents examples of application of the proposed methodology completed as part of the research work. In particular, four experimental applications are described: the first relative to the analysis of twelve product systems of the agri-food sector (§ 4.1); the second relative to a reference product system specifically designed for the research purposes (§ 4.2); the third consisting of a comparative assessment of agricultural processes (conventional and organic) for the production of barley (§ 4.3) based on real data collected in the field; the fourth consisting of an application for the assessment of four beer products carried out within an important Italian company in the beverage industry. Each application is presented following the proposed methodology scheme, addressing where applicable, all the required stages and steps

4.1 Methodology application to agri-food products

The proposed methodology was firstly applied to twelve product systems of the agri-food sector, as regards the first two steps (nitrogen inventory and reactive nitrogen indicator). This choice was made starting from two considerations:

- the agri-food sector, along with the energy sector, is the one that provides the greatest contribution in terms of nitrogen related environmental impacts;
- the nitrogen footprint applications found in literature, to date, are for the most part related to agri-food products: some of these have been used as a comparison for a first validation of the methodology, as described below.

The application was performed using data extracted from professional databases specifically designed for LCA studies. As an important result, this first assessment also allowed to determine the nitrogen-containing substances most likely to be found as output from inventory analysis and to calculate the corresponding nitrogen coefficients.

4.1.1 Agri-food products: goal and scope definition

The goal of this application was to apply the first two steps of the methodology to 12 agri-food products, in order to obtain a result expressed as reactive nitrogen accounted as outflow from the analyzed product systems.

The objectives of the application can be summarized as follows:

- test the first step of the methodology, with reference to the nitrogen inventory results obtaining;
- calculate the reactive nitrogen indicator, starting from the nitrogen inventory results;
- set the method for calculating the nitrogen coefficients and start the iterative accounting process;
- implement an automated calculation procedure, applicable to inventory results, for calculating the reactive nitrogen indicator;
- make an initial validation of the methodology, with reference to the reactive nitrogen indicator calculation, by comparing with published research data referred to nitrogen footprint calculation;
- confirm the validity of the databases used to derive the nitrogen inventory results;
- obtain information related to substances that contribute most to the impact in terms of reactive nitrogen.

4.1.2 Agri-food products: inventory analysis

The methodology was applied to 12 product systems of the agri-food sector as summarized in the Table 4.1 showing, for each product analyzed, the database used for inventory analysis, the name of the selected database record and a short description of the life cycle scope, that allows to quickly evaluate the level of data coverage with reference to the life cycle phases of the analyzed product.

All the data used for the application were obtained from specific life cycle inventory professional databases, as described below.

Table 4.1. *Agri-food products inventory analysis. List of products analyzed, databases and records used for products analysis and data coverage level referred to products life cycle.*

Agri-food product	Source	Database record	Life cycle scope
Barley	Database Ecoinvent ver. 3.1	1 kg barley grain	Market for

Agri-food product	Source	Database record	Life cycle scope
Rice	Database Ecoinvent ver. 3.1	1 kg rice	Market for
Maize	Database Ecoinvent ver. 3.1	1 kg maize seed organic	At farm; referred to the situation in Switzerland
Soybean	Database Ecoinvent ver. 3.1	1 kg soybean seed	For sowing
Tomato	Database Ecoinvent ver. 3.1	1 kg tomato	Market for
Potato	Database Ecoinvent ver. 3.1	1 kg potato	Market for
Sugar beet	Agri-footprint ver. 1.0	1 kg sugar beets fresh	At feed compound plant, referred to a typical farm in Netherlands
Beef fillet	LCA food DK	1 kg beef fillet fresh	Whole sale
Chicken	LCA food DK	1 kg chicken fresh	In supermarket
Pork	LCA food DK	kg pork minced meat	Whole sale
Sheep	Database Ecoinvent ver. 3.1	1 kg sheep for slaughtering live weight	Market for
Egg	LCA food DK	1 kg egg	Not defined

For completeness of information on the inventory phase is provided below the main flow characteristics of the databases used:

- Ecoinvent 3.1. Compiled October 2014. The Ecoinvent v3 database contains LCI data from various sectors such as energy production, transport, building materials, production of chemicals, metal production and fruit and vegetables. The entire database consists of over 10000 interlinked datasets, each of which describes a life cycle inventory on a process level. The system model “allocation, default”, used within this application, contains two methodological choices:
  - it uses the average supply of products, as described in market activity datasets, and
  - it uses partitioning (allocation) to convert multi-product datasets to single-product datasets.

  The flows are allocated relative to their “true value”, which is the economic revenue corrected for some market imperfections and fluctuations.

  References: http://www.ecoinvent.org/; Moreno Ruiz *et al.* (2014).
- LCAfood DK. Provides environmental data on processes in food products product chains and on food products at different stages of their product chains mainly referred to Danish context. Database input/output data on processes in the food sector are derived from a variety of sources. Data on production in agriculture and fishery have been determined by a "top-down" approach

where statistical data on a national level have been broken down to represent specific processes. Data on other processes than agriculture and fishery have been determined by a "bottom-up" approach where data from a limited number of sources have been used to represent the national level. Data include main inputs (resources, raw materials, water and energy) and main outputs (products and waste as well as emissions to air and water). Data do in most cases not include capital goods such as buildings and machinery (except for traction) because it is considered unimportant (except for fishing); packaging, although packaging is highly integrated with food products; cleaning agents and most other chemicals (although it could be relevant in terms of toxicity); veterinary medicine etc.; pesticides, heavy metals etc. Product data have been determined by modeling of process data.

Product models are market based and models include processes, which are influenced by a marginal change in demand for a considered food product. Marginal producers of agricultural products have been determined by modeling in the econometric model. Environmental inputs and outputs associated with food products have been estimated by summarizing inputs and outputs from all production processes in the food products product chains. Total inventories of inputs and outputs associated with food products can be comprehensive and emissions to air and water have been have been recalculated to environmental impact potentials to limit the reporting in the present context.

Many processes in the food sector produce more than one product and environmental emissions associated with specific products have been determined by system expansion. Contributions from different processes as a result of system expansion have been determined analytically by matrix calculations.

Marginal data have been applied for electricity drawn from the public grid.

References: http://gefionau.dk/lcafood/.

- Agri-footprint version 1.0 (May 2014). Includes linked unit process inventories of crop cultivation, crop processing, animal production systems and processing of animal products for multi-impact life cycle assessments. Agri-footprint also contains inventory data on transport, fertilizers production and auxiliary materials.

  For the crops and the processing of the crops, mass allocation is based on the mass of the dry matter of the products. For the animal products, mass allocation is based on the mass as traded.

  References: http://www.agri-footprint.com/; Durlinger *et al.* (2014).

For the analysis, was made use of the professional software for LCA application "SimaPro" in the version 8.3.

As an example of the output obtained with reference to the first step of the methodology, the nitrogen inventory results for 3 of the 12 analyzed product systems are reported in the following tables. For synthesis reasons, the nitrogen inventory results of all other analyzed product systems are not listed: the reported results are however considered sufficiently explanatory and representative of the entire assessment process carried out.

Results reported are expressed as emissions of nitrogen-containing substances in the different environmental compartments (air, water, soil) and are referred to product systems whose functional unit is equal to 1 kg of product. In order to highlight the differences in database records, the results reported for the 3 product systems are calculated using three different reference databases. To select the nitrogen containing substances, a cut-off criterion was applied according to which all outputs were considered whose mass was ≥ 1 ng; some substances considered to be particularly relevant due to potential environmental impacts were however included in the results, also in the case of emissions < 1 ng.

In the Table 4.2 are reported the nitrogen inventory results for the product "barley" obtained using the database Ecoinvent, version 3.1.

Table 4.2. *Nitrogen inventory results for the agri-food product "barley" referred to a functional unit of 1 kg of product. Database used: Ecoinvent 3.1.*

Substance	Compartment	U.o.m.	Nitrogen inventory result
2-Aminopropanol	Air	µg	1.002299
2-Aminopropanol	Water	µg	2.40559
2-Nitrobenzoic acid	Air	µg	2.419804
Acephate	Soil	µg	9.732429
Acetamide	Soil	µg	1.706692
Acetochlor	Soil	µg	20.13639
Acetonitrile	Air	µg	5.258824
Acetonitrile	Water	µg	3.059486
Alachlor	Soil	µg	2.957805
Aldicarb	Soil	µg	32.74457
Ammonia	Air	g	1.460451
Ammonium. ion	Water	mg	18.35426
Aniline	Air	µg	6.337134
Aniline	Water	µg	15.2098
Anthranilic acid	Air	µg	1.885813
Atrazine	Soil	µg	43.85368
Azoxystrobin	Soil	mg	4.483633

Substance	**Compartment**	**U.o.m.**	**Nitrogen inventory result**
Benzene. 1-methyl-2-nitro-	Air	µg	2.089543
Bifenox	Soil	mg	1.061031
Bitertanol	Soil	µg	447.4007
Bromoxynil	Soil	mg	2.663421
Carbetamide	Soil	µg	1.193662
Carbofuran	Soil	µg	2.835621
Carfentrazone-ethyl	Soil	µg	41.42748
Chloramine	Air	µg	14.10739
Chloramine	Water	µg	125.8863
Chlormequat	Soil	µg	107.0086
Chlorothalonil	Soil	µg	3.767397
Chlorpyrifos	Soil	µg	27.40862
Chlortoluron	Soil	mg	6.391707
Clopyralid	Soil	µg	94.69527
Cyanide	Air	µg	157.0211
Cyanide	Water	µg	127.3834
Cyanoacetic acid	Air	µg	3.653724
Cypermethrin	Soil	µg	297.8679
Cyproconazole	Soil	µg	161.9312
Cyprodinil	Soil	mg	12.68111
Deltamethrin	Soil	µg	66.5841
Dicrotophos	Soil	µg	1.786721
Diethylamine	Air	µg	3.020777
Diethylamine	Water	µg	7.249912
Diflubenzuron	Soil	µg	36.04152
Diflufenican	Soil	mg	5.124469
Dimethenamid	Soil	µg	2.132403
Dimethylamine	Water	µg	49.94838
Dinitrogen monoxide	Air	mg	910.2703
Dipropylamine	Air	µg	1.35951
Dipropylamine	Water	µg	3.262915
Diuron	Soil	µg	2.746602
Epoxiconazole	Soil	µg	914.3735
Ethylamine	Air	µg	3.62426
Ethylamine	Water	µg	8.698271
Ethylene diamine	Water	µg	1.88849
Fenoxaprop-P ethyl ester	Soil	µg	307.7475
Fenpropidin	Soil	mg	13.51554
Fenpropimorph	Soil	mg	2.123867
Fipronil	Soil	µg	10.77756
Florasulam	Soil	µg	112.6293
Fludioxonil	Soil	µg	265.1377
Flufenacet	Soil	mg	4.505171
Fluroxypyr	Soil	µg	189.3842
Flurtamone	Soil	mg	4.693201
Flusilazole	Soil	µg	512.6584
Formamide	Air	µg	6.01966
Formamide	Water	µg	14.44739
Glyphosate	Air	µg	2.948826

Substance	**Compartment**	**U.o.m.**	**Nitrogen inventory result**
Glyphosate	Soil	µg	166.2244
Imidacloprid	Soil	mg	2.098389
Ioxynil	Soil	mg	1.598013
Isocyanic acid	Air	µg	51.85632
Isopropylamine	Air	µg	1.746417
Isopropylamine	Water	µg	4.191423
Isoproturon	Soil	mg	27.79938
Kresoxim-methyl	Soil	µg	40.65336
Lambda-cyhalothrin	Soil	µg	517.188
Linuron	Soil	µg	5.354633
Mancozeb	Soil	µg	3.317876
Mefenpyr	Soil	mg	1.099592
Mefenpyr-diethyl	Soil	µg	615.5111
Mepiquat chloride	Soil	mg	4.341424
Metamitron	Soil	µg	34.10154
Methylamine	Air	µg	2.080833
Methylamine	Water	µg	4.994011
Metolachlor	Soil	µg	27.12661
Monocrotophos	Soil	µg	4.403188
Monoethanolamine	Air	µg	377.75
Napropamide	Soil	µg	1.045052
Nitrate	Air	µg	27.41394
Nitrate	Water	g	53.37498
Nitrate	Soil	µg	41.9138
Nitrite	Water	µg	218.8499
Nitrobenzene	Air	µg	10.05509
Nitrobenzene	Water	µg	40.29569
Nitrogen	Water	mg	8.968842
Nitrogen	Soil	µg	1.871878
Nitrogen oxides	Air	g	2.128166
Nitrogen. organic bound	Water	mg	6.662707
Particulates. < 2.5 µm	Air	mg	303.8753
Particulates. > 2.5 µm. and < 10µm	Air	mg	120.8795
Pendimethalin	Soil	µg	6.794144
Phenmedipham	Soil	µg	6.248982
Propiconazole	Soil	mg	5.07422
Propylamine	Water	µg	1.33194
t-Butylamine	Air	µg	3.537753
t-Butylamine	Water	µg	8.490666
Tebutam	Soil	µg	3.326275
Tralkoxydim	Soil	mg	10.51068
Trifloxystrobin	Soil	µg	608.1098
Trifluralin	Soil	µg	9.643556
Trimethylamine	Air	µg	1.179393
Trimethylamine	Water	µg	2.830544
Urea	Water	µg	5.270396

In the Table 4.3 are reported the nitrogen inventory results for the product “sugar beet” obtained using the database Agri-footprint version 1.0.

Table 4.3. *Nitrogen inventory results for the agri-food product “sugar beet” referred to a functional unit of 1 kg of product. Database used: Agri-footprint 1.0.*

Substance	Compartment	U.o.m.	Nitrogen inventory result
Acrylonitrile	Water	pg	17.0876054
Ammonia	Air	mg	475.879292
Ammonia	Water	µg	19.4836463
Ammonia	Soil	µg	316.978576
Ammonium, ion	Air	pg	5.53437746
Chloridazon	Soil	mg	6.32332447
Clopyralid	Soil	µg	208.789015
Cyanide	Air	ng	180.347268
Cyanide	Water	ng	77.4846393
Desmedipham	Soil	µg	637.104767
Diethylamine	Air	pg	0.00013062
Dimethenamid	Soil	mg	1.28852649
Dinitrogen monoxide	Air	mg	76.0575679
Epoxiconazole	Soil	mg	3.82978708
Imidacloprid	Soil	mg	1.17757005
Metamitron	Soil	mg	19.6858214
Metolachlor	Soil	mg	5.66713042
Nitrate	Water	g	3.51494763
Nitric oxide	Air	pg	52.3897503
Nitrogen	Water	µg	58.4748466
Nitrogen dioxide	Air	mg	6.62035829
Nitrogen oxides	Air	mg	110.757204
Particulates, < 10 µm	Air	µg	885.654245
Particulates, < 10 µm	Water	ng	62.0230994
Particulates, < 2.5 µm	Air	mg	2.76807548
Particulates, > 2.5 µm, and < 10µm	Air	mg	1.80660368
Phenmedipham	Soil	mg	2.12368256

In the Table 4.4 are reported the nitrogen inventory results for the product “egg” obtained using the database LCAfood DK.

Table 4.4. *Nitrogen inventory results for the agri-food product “egg” referred to a functional unit of 1 kg of product. Database used: LCAfood DK.*

Substance	Compartment	U.o.m.	Nitrogen inventory result
Ammonia	Air	g	20.963461
Ammonia, as N	Water	mg	5.0318212

Substance	Compartment	U.o.m.	Nitrogen inventory result
Cyanide	Air	ng	825.21178
Cyanide	Water	µg	26.077922
Dinitrogen monoxide	Air	g	4.2988171
Nitrate	Water	g	96.927493
Nitrite	Water	µg	7.3324117
Nitrogen	Soil	µg	3.8604462
Nitrogen oxides	Air	g	3.3633949
Nitrogen, organic bound	Water	µg	994.34219
Nitrogen, total	Water	mg	6.6090498
Particulates, < 10 µm (mobile)	Air	mg	52.297596
Particulates, < 10 µm (stationary)	Air	mg	23.323336

The different degree of detail of the database used is evident to a first analysis of the records reported relating to nitrogen-containing substances emissions. In particular, for the product systems analyzed in this application, the database Ecoinvent 3.1 is much more complete as it contains inventories that on average comprise over 1400 results, compared to around 400 results of databases Agri-footprint 1.0 and LCAfood DK.

4.1.3 Agri-food products: assessment at inventory level

Starting from the nitrogen inventory results, the reactive nitrogen indicator was calculated for the 12 product systems, after calculating the nitrogen coefficient for the nitrogen containing substances obtained as output from the inventory analysis.

As an example, the whole calculation reports are shown for 2 of the 12 analyzed product systems. Even in this case, for brevity, the calculation reports of all the analyzed product systems are not listed, only reporting the final results in terms of reactive nitrogen indicator.

The results of the calculation report of the reactive nitrogen indicator for the agri-food product “barley” are reported in the Table 4.5.

Table 4.5. *Calculation report of reactive nitrogen indicator for the agri-food product “barley” listing the nitrogen-containing substances, the compartment of emission, the emitted amount, the calculated nitrogen coefficient and the calculated amount of reactive nitrogen. The indicator result for the whole product system is reported in the last row.*

Substance	Compartment	Nitrogen inventory result [g/kg]	Nitrogen coefficient	Reactive nitrogen [g/kg]
2-Aminopropanol	Air	1.00E-06	0.186	1.87E-07
2-Aminopropanol	Water	2.41E-06	0.186	4.49E-07

Substance	Compartment	Nitrogen inventory result [g/kg]	Nitrogen coefficient	Reactive nitrogen [g/kg]
2-Nitrobenzoic acid	Air	2.42E-06	0.084	2.03E-07
Acephate	Soil	9.73E-06	0.076	7.44E-07
Acetamide	Soil	1.71E-06	0.237	4.05E-07
Acetochlor	Soil	2.01E-05	0.052	1.05E-06
Acetonitrile	Air	5.26E-06	0.341	1.79E-06
Acetonitrile	Water	3.06E-06	0.341	1.04E-06
Alachlor	Soil	2.96E-06	0.052	1.54E-07
Aldicarb	Soil	3.27E-05	0.147	4.82E-06
Ammonia	Air	1.46E+00	0.822	1.20E+00
Ammonium. ion	Water	1.84E-02	0.776	1.43E-02
Aniline	Air	6.34E-06	0.150	9.53E-07
Aniline	Water	1.52E-05	0.150	2.29E-06
Anthranilic acid	Air	1.89E-06	0.102	1.93E-07
Atrazine	Soil	4.39E-05	0.325	1.42E-05
Azoxystrobin	Soil	4.48E-03	0.104	4.67E-04
Benzene. 1-methyl-2-nitro-	Air	2.09E-06	0.102	2.13E-07
Bifenox	Soil	1.06E-03	0.041	4.34E-05
Bitertanol	Soil	4.47E-04	0.125	5.57E-05
Bromoxynil	Soil	2.66E-03	0.051	1.35E-04
Carbetamide	Soil	1.19E-06	0.119	1.42E-07
Carbofuran	Soil	2.84E-06	0.063	1.80E-07
Carfentrazone-ethyl	Soil	4.14E-05	0.102	4.22E-06
Chloramine	Air	1.41E-05	0.272	3.84E-06
Chloramine	Water	1.26E-04	0.272	3.43E-05
Chlormequat	Soil	1.07E-04	0.114	1.22E-05
Chlorothalonil	Soil	3.77E-06	0.105	3.97E-07
Chlorpyrifos	Soil	2.74E-05	0.040	1.10E-06
Chlortoluron	Soil	6.39E-03	0.132	8.42E-04
Clopyralid	Soil	9.47E-05	0.073	6.91E-06
Cyanide	Air	1.57E-04	0.538	8.45E-05
Cyanide	Water	1.27E-04	0.538	6.86E-05
Cyanoacetic acid	Air	3.65E-06	0.165	6.02E-07
Cypermethrin	Soil	2.98E-04	0.034	1.00E-05
Cyproconazole	Soil	1.62E-04	0.144	2.33E-05
Cyprodinil	Soil	1.27E-02	0.187	2.37E-03
Deltamethrin	Soil	6.66E-05	0.028	1.85E-06
Dicrotophos	Soil	1.79E-06	0.059	1.06E-07
Diethylamine	Air	3.02E-06	0.192	5.79E-07
Diethylamine	Water	7.25E-06	0.192	1.39E-06
Diflubenzuron	Soil	3.60E-05	0.090	3.25E-06
Diflufenican	Soil	5.12E-03	0.071	3.64E-04
Dimethenamid	Soil	2.13E-06	0.051	1.08E-07
Dimethylamine	Water	4.99E-05	0.311	1.55E-05
Dinitrogen monoxide	Air	9.10E-01	0.636	5.79E-01
Dipropylamine	Air	1.36E-06	0.138	1.88E-07
Dipropylamine	Water	3.26E-06	0.138	4.52E-07
Diuron	Soil	2.75E-06	0.120	3.30E-07
Epoxiconazole	Soil	9.14E-04	0.127	1.17E-04

Substance	**Compartment**	**Nitrogen inventory result [g/kg]**	**Nitrogen coefficient**	**Reactive nitrogen [g/kg]**
Ethylamine	Air	3.62E-06	0.311	1.13E-06
Ethylamine	Water	8.70E-06	0.311	2.70E-06
Ethylene diamine	Water	1.89E-06	0.466	8.80E-07
Fenoxaprop-P ethyl ester	Soil	3.08E-04	0.039	1.19E-05
Fenpropidin	Soil	1.35E-02	0.051	6.92E-04
Fenpropimorph	Soil	2.12E-03	0.046	9.80E-05
Fipronil	Soil	1.08E-05	0.128	1.38E-06
Florasulam	Soil	1.13E-04	0.195	2.20E-05
Fludioxonil	Soil	2.65E-04	0.113	2.99E-05
Flufenacet	Soil	4.51E-03	0.116	5.21E-04
Fluroxypyr	Soil	1.89E-04	0.110	2.08E-05
Flurtamone	Soil	4.69E-03	0.042	1.97E-04
Flusilazole	Soil	5.13E-04	0.133	6.83E-05
Formamide	Air	6.02E-06	0.311	1.87E-06
Formamide	Water	1.44E-05	0.311	4.49E-06
Glyphosate	Air	2.95E-06	0.083	2.44E-07
Glyphosate	Soil	1.66E-04	0.083	1.38E-05
Imidacloprid	Soil	2.10E-03	0.274	5.75E-04
Ioxynil	Soil	1.60E-03	0.038	6.03E-05
Isocyanic acid	Air	5.19E-05	0.326	1.69E-05
Isopropylamine	Air	1.75E-06	0.237	4.14E-07
Isopropylamine	Water	4.19E-06	0.237	9.93E-07
Isoproturon	Soil	2.78E-02	0.136	3.78E-03
Kresoxim-methyl	Soil	4.07E-05	0.045	1.82E-06
Lambda-cyhalothrin	Soil	5.17E-04	0.031	1.61E-05
Linuron	Soil	5.35E-06	0.112	6.02E-07
Mancozeb	Soil	3.32E-06	0.104	3.44E-07
Mefenpyr	Soil	1.10E-03	0.088	9.71E-05
Mefenpyr-diethyl	Soil	6.16E-04	0.075	4.62E-05
Mepiquat chloride	Soil	4.34E-03	0.094	4.06E-04
Metamitron	Soil	3.41E-05	0.277	9.45E-06
Methylamine	Air	2.08E-06	0.451	9.38E-07
Methylamine	Water	4.99E-06	0.451	2.25E-06
Metolachlor	Soil	2.71E-05	0.049	1.34E-06
Monocrotophos	Soil	4.40E-06	0.063	2.76E-07
Monoethanolamine	Air	3.78E-04	0.229	8.66E-05
Napropamide	Soil	1.05E-06	0.052	5.39E-08
Nitrate	Air	2.74E-05	0.226	6.19E-06
Nitrate	Water	5.34E+01	0.226	1.21E+01
Nitrate	Soil	4.19E-05	0.226	9.47E-06
Nitrite	Water	2.19E-04	0.304	6.66E-05
Nitrobenzene	Air	1.01E-05	0.114	1.14E-06
Nitrobenzene	Water	4.03E-05	0.114	4.58E-06
Nitrogen	Water	8.97E-03	1.000	8.97E-03
Nitrogen	Soil	1.87E-06	1.000	1.87E-06
Nitrogen oxides	Air	2.13E+00	0.304	6.48E-01
Nitrogen. organic bound	Water	6.66E-03	0.160	1.07E-03
Particulates. < 2.5µm	Air	3.04E-01	0.081	2.45E-02

Substance	**Compartment**	**Nitrogen inventory result [g/kg]**	**Nitrogen coefficient**	**Reactive nitrogen [g/kg]**
Particulates. > 2.5µm. and < 10µm	Air	1.21E-01	0.028	3.37E-03
Pendimethalin	Soil	6.79E-06	0.149	1.01E-06
Phenmedipham	Soil	6.25E-06	0.093	5.83E-07
Propiconazole	Soil	5.07E-03	0.123	6.23E-04
Propylamine	Water	1.33E-06	0.237	3.16E-07
t-Butylamine	Air	3.54E-06	0.192	6.78E-07
t-Butylamine	Water	8.49E-06	0.192	1.63E-06
Tebutam	Soil	3.33E-06	0.060	2.00E-07
Tralkoxydim	Soil	1.05E-02	0.043	4.47E-04
Trifloxystrobin	Soil	6.08E-04	0.069	4.17E-05
Trifluralin	Soil	9.64E-06	0.125	1.21E-06
Trimethylamine	Air	1.18E-06	0.237	2.79E-07
Trimethylamine	Water	2.83E-06	0.237	6.71E-07
Urea	Water	5.27E-06	0.466	2.46E-06
Total product system	-	-	-	**1.46E+01**

By analyzing the results obtained from the calculation of the reactive nitrogen indicator, it is possible to identify which emitted substances give the largest contribution in terms of reactive nitrogen for the product systems. In particular, the Figure 4.1 shows the he main substances that contribute to the total impact, in terms of reactive nitrogen, for the agri-food product “barley”, presenting the contribution of each substance expressed as a percentage of the total reactive nitrogen calculated for the product system.

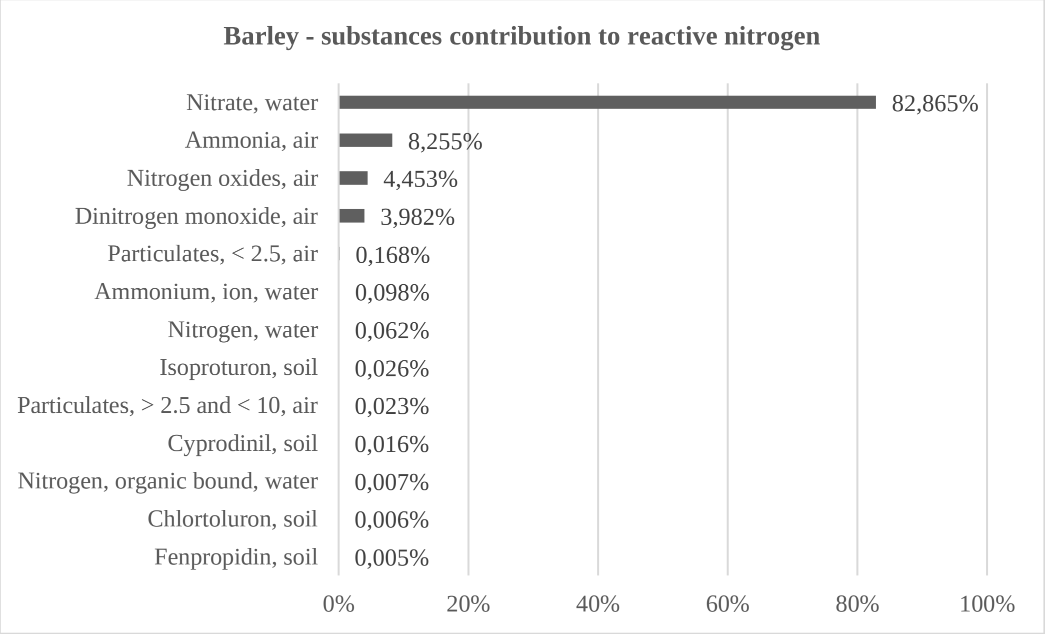


Figure 4.1. *Substances contribution (percentage ≥ 0.005 %) to the product system impact expressed as reactive nitrogen with reference to the agri-food product "barley".*

The results obtained for the specific product system are indicative of all the analyzed agri-food products, in particular with regard to the contribution of emissions of nitrate in the compartment water, ammonia in the compartment air, nitrogen oxides in the compartment air and dinitrogen monoxide in the compartment air that are the most significant for all the products. Nitrate emissions to water are always the biggest contributor, with percentages that, for all products analyzed, exceed 50% of the total reactive nitrogen.

As a second example, the results of the calculation report of the reactive nitrogen indicator for the agri-food product "sugar beet" are reported in the Table 4.6.

Table 4.6. *Calculation report of reactive nitrogen indicator for the agri-food product "sugar beet" listing the nitrogen-containing substances, the compartment of emission, the emitted amount, the calculated nitrogen coefficient and the calculated amount of reactive nitrogen. The indicator result for the whole product system is reported in the last row.*

Substance	Compartment	Nitrogen inventory result [g/kg]	Nitrogen coefficient	Reactive nitrogen [g/kg]
Acrylonitrile	Water	1.71E-11	0.264	4.51E-12
Ammonia	Air	4.76E-01	0.822	3.91E-01
Ammonia	Water	1.95E-05	0.822	1.60E-05
Ammonia	Soil	3.17E-04	0.822	2.61E-04
Ammonium, ion	Air	5.53E-12	0.776	4.30E-12
Chloridazon	Soil	6.32E-03	0.190	1.20E-03
Clopyralid	Soil	2.09E-04	0.073	1.52E-05
Cyanide	Air	1.80E-07	0.538	9.71E-08
Cyanide	Water	7.75E-08	0.538	4.17E-08
Desmedipham	Soil	6.37E-04	0.093	5.94E-05
Diethylamine	Air	1.31E-16	0.192	2.50E-17
Dimethenamid	Soil	1.29E-03	0.051	6.54E-05
Dinitrogen monoxide	Air	7.61E-02	0.636	4.84E-02
Epoxiconazole	Soil	3.83E-03	0.127	4.88E-04
Imidacloprid	Soil	1.18E-03	0.274	3.23E-04
Metamitron	Soil	1.97E-02	0.277	5.45E-03
Metolachlor	Soil	5.67E-03	0.049	2.80E-04
Nitrate	Water	3.51E+00	0.226	7.94E-01
Nitric oxide	Air	5.24E-11	0.467	2.45E-11
Nitrogen	Water	5.85E-05	1.000	5.85E-05
Nitrogen dioxide	Air	6.62E-03	0.304	2.02E-03
Nitrogen oxides	Air	1.11E-01	0.304	3.37E-02
Particulates, < 10 μm	Air	8.86E-04	0.054	4.80E-05
Particulates, < 10 μm	Water	6.20E-08	0.054	3.36E-09
Particulates, < 2.5 μm	Air	2.77E-03	0.081	2.23E-04

Substance	Compartment	Nitrogen inventory result [g/kg]	Nitrogen coefficient	Reactive nitrogen [g/kg]
Particulates, > 2.5 µm, and < 10µm	Air	1.81E-03	0.028	5.04E-05
Phenmedipham	Soil	2.12E-03	0.093	1.98E-04
Total product system	-	-	-	**1.28E+00**

The final results of the calculation of the reactive nitrogen indicator for all the 12 agri-food products analyzed are reported in the Table 4.7.

Table 4.7. *Reactive nitrogen indicator results [g/kg] for the 12 product systems of the agri-food sector analyzed.*

Agri-food product	Functional unit	Reactive nitrogen indicator result [g/funct. unit]
Barley	1 kg	14.550
Rice	1 kg	15.000
Maize	1 kg	36.322
Soybean	1 kg	16.226
Tomato	1 kg	2.195
Potato	1 kg	3.872
Sugar beet	1 kg	1.278
Beef fillet	1 kg	920.617
Chiken	1 kg	45.978
Pork	1 kg	62.496
Sheep	1 kg	178.336
Egg	1 kg	42.912

During the testing phase, an automatic calculation procedure was also developed, which, starting from the inventory analysis results, allows selecting the nitrogen-containing substances, associating the related nitrogen coefficients and calculating the reactive nitrogen indicator results, thus significantly decreasing the time of calculation.

4.1.4 Agri-food products: interpretation of the results

As a first element on the interpretation of the results, is considered appropriate to highlight the validation process carried out with reference to the output of the first part of the methodology. Specifically, the reactive nitrogen indicator results have been compared with some published research results related to the nitrogen footprint calculation. The reactive nitrogen indicator, included as part of the proposed methodology in the step of the assessment at inventory level, is, in fact, assimilable to the current definition of “nitrogen footprint”, even though it is calculated with a different and innovative approach.

In the Table 4.8 are reported the outcomes of the comparison between the results of the reactive nitrogen indicator calculated for the 12 agri-food products, which were also functionally chosen for this purpose, and some results of nitrogen footprint calculation found in literature published researches.

Table 4.8. *Outcomes of validation process: comparison between calculated reactive nitrogen indicator results and literature results for nitrogen footprint accounting. Reference for literature results: (1) CAPRI model average results for food categories, Leip et al. (2014a); (2) MITERRA model average results for food categories, Leip et al. (2014a); (3) China double rice results, Xue et al. (2016). Matching degree considered range*: lower - upper quartiles (only for results of Leip et al., 2014a).*

Agri-food product	Reactive nitrogen indicator calculation results [g/kg]	Nitrogen footprint literature results [g/kg]	Matching degree
Barley	14.550	≈14(1); ≈8(2)	medium-high (within the range*)
Rice	15.000	≈14(1); ≈8(2); 10.5-10.8(3)	medium-high (within the range*)
Maize	36.322	≈14(1); ≈8(2)	sufficient (< maximum of the sample*)
Soybean	16.226	≈21(1); ≈19(2)	medium-high (within the range*)
Tomato	2.195	≈2(1); ≈3.5(2)	high (within the range*)
Potato	3.872	≈3(1); ≈2(2)	medium-high (within the range*)
Sugar beet	1.278	≈2.5(1); ≈2(2)	medium-high (within the range*)
Beef fillet	920.617	≈550(1); ≈490(2)	low (> maximum of the sample*)
Chicken	45.978	≈65(1); ≈100(2)	sufficient (within the range*)
Pork	62.496	≈120(1); ≈125(2)	low (< minimum of the sample*)
Sheep	178.336	≈500(1); ≈600(2)	low (< minimum of the sample*)
Egg	42.912	≈45(1); ≈70(2)	medium-high (within the range*)

While the different methodological approaches used for the calculation, the comparison results were satisfactory, showing a high and medium high degree of correspondence for 7 of the 12 products, a sufficient degree for 2 products and a low degree for 3 products. Ecoinvent 3.1 was also found to be the most reliable database, as well as the more complete, as above highlighted. It should be pointed out that, as with all LCA applications, the choice of database entries to be used for analysis is a process that requires particular attention and care in relation to the defined goal and scope of the application and to the established data level of quality. The results above presented are therefore considered to be indicative: further deepening and analysis of databases, which are outside the scope of the research, would be needed in order to provide more reliable data.

With regard to other achievements, in relation to the objectives initially set out, the following are highlighted:

- The first steps of the methodology were successfully tested by performing the calculation of nitrogen inventory results and reactive nitrogen indicator for 12 agri-food products using data from internationally applied and recognized databases for LCA studies. As for the results obtained, products of animal origin have the highest values of reactive nitrogen indicator, especially with reference to ruminant meat, while the indicator for all other products resulted considerably lower, with a consistent ranking of the product pork, poultry meat and eggs. For the vegetable products, the cereals and oilseeds obtained similar results (slightly higher for oilseeds), with the exception of maize for which a higher value was calculated, probably related to the specific database record which refers to a specific geographic context (Switzerland). Lower values were found for potato, tomato and sugar beet. These results are congruent with what emerged in several researches conducted, and in particular with what highlighted by Leip *et al.* (2014a) in reference to the nitrogen footprint of food products in the European Union.
- As part of the specific application, and of the whole methodology, the nitrogen coefficient calculation procedure was set, starting the coefficients iterative accounting; within the research applications, this procedure was used to calculate the value of the coefficients of more than 200 nitrogen-containing substances detected as output streams from the analyzed product systems within the nitrogen inventory results.
- As above highlighted, an automatic database calculation procedure was developed and tested for reactive nitrogen indicator accounting starting from inventory results, achieving a remarkable reduction in computing times and an increase in efficiency in the application of the entire methodology and in the analysis of results.
- The application also allowed testing and confirming the validity of the databases used to derive the nitrogen inventory results, in particular highlighting greater completeness and reliability for the data contained in the professional database Ecoinvent 3.1.

- This first testing phase, finally, allowed to obtain information on the output streams of substances that produce the greatest impact measured in terms of reactive nitrogen for the analyzed product systems, in particular by identifying as the most significant the flows of nitrate in water, ammonia, nitrogen oxides and dinitrogen monoxide in air.

4.2 Methodology application to a reference product system

During the experimentation phase, the proposed methodology was applied to a reference product system specifically created for the purposes the research, consisting in the union of ten product categories each comprising four products for a total of 40 product systems, as described below in this section.

4.2.1 Reference product system: goal and scope definition

The experimental application described in this section relates to a reference product system specifically created in order to achieve the following objectives:

- test the whole methodology, with reference to all the phase and operative step provided;
- calculate a specific weighting set, obtained by applying the internal weighting method, included in the proposed methodology, to the reference product system, in order to be used as an alternative reference set also for subsequent applications of the methodology.

The products to be included in the system were chosen to be sufficiently representative of an average collection, focusing in particular on the categories related to the food sector, which is the one that provides the greatest contribution in terms of nitrogen-related environmental impacts.

4.2.2 Reference product system: inventory analysis

The 10 product categories, each comprising four product systems are described in the Table 4.9 reporting the considered product categories, the products included, the database used for the inventory, the selected functional unit and a short description of the life cycle scope, to quickly evaluate the level of inventory data coverage with reference to the life cycle phases of the analyzed product.

Table 4.9. *Reference product system inventory analysis: list of product categories and products analyzed, databases used, functional unit and data coverage level referred to products life cycle.*

Product category	Product	Database	Functional unit	Life cycle scope
vegetables	zucchini	Ecoinvent 3.1	1 kg	market for
vegetables	tomato	Ecoinvent 3.1	1 kg	market for
vegetables	potato	Ecoinvent 3.1	1 kg	market for
vegetables	onion	Ecoinvent 3.1	1 kg	market for
textiles	jute	Ecoinvent 3.1	1 kg	market for
textiles	knit cotton	Ecoinvent 3.1	1 kg	market for
textiles	viscose fibre	Ecoinvent 3.1	1 kg	market for
textiles	woven cotton	Ecoinvent 3.1	1 kg	market for
vegetable oils	coconut oil	Ecoinvent 3.1	1 kg	market for
vegetable oils	palm oil	Ecoinvent 3.1	1 kg	market for
vegetable oils	rape oil	Ecoinvent 3.1	1 kg	market for
vegetable oils	vegetable oil	Ecoinvent 3.1	1 kg	market for
metals	steel, chromium 18/8	Ecoinvent 3.1	1 kg	market for
metals	steel, unalloyed	Ecoinvent 3.1	1 kg	market for
metals	aluminum, primary, ingot	Ecoinvent 3.1	1 kg	market for
metals	copper	Ecoinvent 3.1	1 kg	market for
meat	chicken, fresh	LCAfood DK	1 kg	whole sale
meat	beef steak, fresh	LCAfood DK	1 kg	whole sale
meat	pork neck	LCAfood DK	1 kg	whole sale
meat	ham	LCAfood DK	1 kg	whole sale
fuels	diesel	Ecoinvent 3.1	1 kg	market for
fuels	petrol, unleaded	Ecoinvent 3.1	1 kg	market for
fuels	natural gas, high pressure	Ecoinvent 3.1	1 kg	at service station
fuels	fuel oil	LCAfood DK	1 kg	not defined
fruit	apple	Ecoinvent 3.1	1 kg	market for
fruit	melon	Ecoinvent 3.1	1 kg	market for
fruit	kiwi	Ecoinvent 3.1	1 kg	market for
fruit	grape	Ecoinvent 3.1	1 kg	market for
fish	cod, fresh	LCAfood DK	1 kg	whole sale
fish	flatfish, fresh	LCAfood DK	1 kg	whole sale
fish	mussels, fresh	LCAfood DK	1 kg	whole sale
fish	trout, frozen	LCAfood DK	1 kg	whole sale
dairy	butter	Ecoinvent 3.1	1 kg	whole sale
dairy	cheese	Ecoinvent 3.1	1 kg	whole sale
dairy	cream, 38%	Ecoinvent 3.1	1 kg	whole sale
dairy	full milk	Ecoinvent 3.1	1 kg	whole sale
cereals	barley grain	Ecoinvent 3.1	1 kg	market for
cereals	maize grain	Ecoinvent 3.1	1 kg	market for
cereals	rice	Ecoinvent 3.1	1 kg	market for
cereals	wheat grain	Ecoinvent 3.1	1 kg	market for

The results of the nitrogen inventory analysis are not reported here because they are explicitated in the reactive nitrogen calculation report presented in the following paragraph.

As in the previous application example, concerning the agri-food products analysis, also the data used for this application were entirely derived from the professional life cycle inventory databases indicated in the above reported list of the Table 4.9.

4.2.3 Reference product system: assessment at inventory level

The first steps of the methodology consists in the calculation of nitrogen inventory results and reactive nitrogen indicator. Also for this application, to calculate the nitrogen inventory results, starting from the complete inventory, a mass cut-off criterion with an overall threshold set to 1 ng was applied, however including substances with fewer emissions considered to be particularly relevant due to potential environmental impacts. The results of the calculation are reported in the Table 4.10 in which the first column lists the nitrogen-containing substances selected starting from the inventory results and the last column shows the reactive nitrogen calculated for each emitted substance.

For completeness the value of calculated reactive nitrogen indicator for the entire product system was also reported in the last row of the Table 4.10: this value is however not indicative of any specific product and is not even functional for subsequent calculations, only the results related to the emitted substances being subsequently o be used for the calculation of the weighting set.

Table 4.10. *Calculation report of reactive nitrogen indicator for the reference product system listing the nitrogen-containing substances, the compartment of emission, the emitted amount, the calculated nitrogen coefficient and the calculated amount of reactive nitrogen. The indicator result for the whole product system is reported in the last row.*

Substance	Compartment	Nitrogen inventory result [g]	Nitrogen coefficient	Reactive nitrogen [g]
2-Aminopropanol	Air	1.60E-04	0.186	2.99E-05
2-Aminopropanol	Water	3.85E-04	0.186	7.18E-05
2-Nitrobenzoic acid	Air	7.71E-05	0.084	6.47E-06
Acephate	Air	8.05E-05	0.076	6.16E-06
Acephate	Soil	1.45E-01	0.076	1.11E-02
Acetamide	Air	1.98E-05	0.237	4.70E-06
Acetamide	Soil	2.13E-02	0.237	5.05E-03
Acetochlor	Soil	5.96E-02	0.052	3.10E-03
Acetonitrile	Air	5.39E-02	0.341	1.84E-02
Acetonitrile	Water	5.43E-05	0.341	1.85E-05
Acifluorfen	Air	1.11E-05	0.039	4.28E-07
Acifluorfen	Soil	4.74E-07	0.039	1.84E-08
Aclonifen	Soil	1.81E-07	0.106	1.92E-08
Alachlor	Air	7.82E-05	0.052	4.06E-06
Alachlor	Soil	4.23E-03	0.052	2.19E-04
Aldicarb	Soil	4.91E-01	0.147	7.23E-02
Amidosulfuron	Soil	1.50E-08	0.190	2.83E-09
Ammonia	Air	3.30E+02	0.822	2.71E+02
Ammonia, as N	Water	3.01E-01	1.000	3.01E-01
Ammonium carbonate	Air	2.98E-05	0.292	8.68E-06
Ammonium, ion	Water	5.13E+00	0.776	3.98E+00
Aniline	Air	2.28E-03	0.150	3.44E-04
Aniline	Water	5.48E-03	0.150	8.25E-04

Substance	**Compartment**	**Nitrogen inventory result [g]**	**Nitrogen coefficient**	**Reactive nitrogen [g]**
Anthranilic acid	Air	5.98E-05	0.102	6.10E-06
Asulam	Soil	4.64E-05	0.122	5.64E-06
Atrazine	Air	6.19E-05	0.325	2.01E-05
Atrazine	Soil	1.13E-01	0.325	3.66E-02
Azinphos-methyl	Soil	3.96E-04	0.132	5.24E-05
Azoxystrobin	Air	3.66E-05	0.104	3.81E-06
Azoxystrobin	Soil	9.03E-03	0.104	9.40E-04
Benfluralin	Soil	9.55E-02	0.125	1.20E-02
Benomyl	Soil	2.04E-04	0.193	3.95E-05
Bensulfuron methyl ester	Soil	1.26E-03	0.137	1.72E-04
Bentazone	Air	3.38E-05	0.117	3.94E-06
Bentazone	Soil	4.07E-03	0.117	4.74E-04
Benzene, 1-methyl-2-nitro-	Air	6.66E-05	0.102	6.80E-06
Benzene, pentachloronitro-	Soil	4.08E-03	0.047	1.94E-04
Bifenox	Soil	1.65E-03	0.041	6.76E-05
Bitertanol	Soil	3.70E-05	0.125	4.61E-06
Bromoxynil	Soil	6.90E-03	0.051	3.49E-04
Bromuconazole	Soil	1.12E-04	0.111	1.24E-05
Captan	Soil	2.54E-01	0.047	1.18E-02
Carbaryl	Air	9.23E-06	0.070	6.43E-07
Carbaryl	Soil	1.45E-03	0.070	1.01E-04
Carbendazim	Soil	8.19E-03	0.220	1.80E-03
Carbetamide	Soil	1.73E-01	0.119	2.05E-02
Carbofuran	Soil	1.14E-01	0.063	7.22E-03
Carfentrazone-ethyl	Air	1.01E-06	0.102	1.03E-07
Carfentrazone-ethyl	Soil	3.40E-05	0.102	3.46E-06
Chloramine	Air	7.44E-04	0.272	2.02E-04
Chloramine	Water	6.64E-03	0.272	1.81E-03
Chloridazon	Soil	9.96E-03	0.190	1.89E-03
Chlorimuron-ethyl	Air	1.85E-05	0.135	2.49E-06
Chlorimuron-ethyl	Soil	5.10E-04	0.135	6.89E-05
Chlormequat	Soil	5.52E-02	0.114	6.31E-03
Chlorothalonil	Soil	5.95E-02	0.105	6.27E-03
Chlorpyrifos	Air	3.68E-04	0.040	1.47E-05
Chlorpyrifos	Soil	4.00E-01	0.040	1.60E-02
Chlorsulfuron	Soil	1.54E-04	0.196	3.01E-05
Chlortoluron	Soil	1.16E-05	0.132	1.53E-06
Choline chloride	Soil	2.12E-02	0.100	2.13E-03
Cinidon-ethyl	Soil	1.81E-08	0.036	6.44E-10
Clethodim	Air	5.46E-05	0.039	2.13E-06
Clethodim	Soil	7.33E-04	0.039	2.85E-05
Clodinafop-propargyl	Soil	2.28E-03	0.040	9.12E-05
Clomazone	Soil	2.36E-02	0.058	1.38E-03
Clopyralid	Soil	1.61E-03	0.073	1.18E-04
Cloquintocet-mexyl	Soil	5.50E-04	0.042	2.29E-05
Cloransulam-methyl	Air	9.62E-06	0.163	1.57E-06
Cloransulam-methyl	Soil	2.19E-04	0.163	3.57E-05
Cyanide	Air	1.11E+00	0.538	5.98E-01

Substance	Compartment	Nitrogen inventory result [g]	Nitrogen coefficient	Reactive nitrogen [g]
Cyanide	Water	2.04E-01	0.538	1.10E-01
Cyanoacetic acid	Air	6.49E-05	0.165	1.07E-05
Cycloxydim	Soil	2.38E-10	0.043	1.02E-11
Cyfluthrin	Air	1.93E-06	0.032	6.22E-08
Cyfluthrin	Soil	1.52E-03	0.032	4.90E-05
Cyhalothrin, gamma-	Air	2.21E-05	0.031	6.89E-07
Cyhalothrin, gamma-	Soil	9.48E-07	0.031	2.95E-08
Cymoxanil	Soil	9.18E-03	0.283	2.60E-03
Cypermethrin	Air	4.68E-06	0.034	1.57E-07
Cypermethrin	Soil	4.63E-02	0.034	1.56E-03
Cyproconazole	Soil	9.03E-04	0.144	1.30E-04
Cyprodinil	Soil	1.34E-02	0.187	2.50E-03
Deltamethrin	Soil	2.71E-04	0.028	7.50E-06
Diazinon	Soil	1.40E-02	0.092	1.29E-03
Dicrotophos	Soil	2.66E-02	0.059	1.57E-03
Diethylamine	Air	1.13E-03	0.192	2.17E-04
Diethylamine	Water	2.72E-03	0.192	5.21E-04
Difenoconazole	Soil	3.98E-02	0.103	4.12E-03
Diflubenzuron	Air	1.01E-06	0.090	9.15E-08
Diflubenzuron	Soil	1.45E-01	0.090	1.31E-02
Diflufenican	Soil	3.62E-03	0.071	2.57E-04
Diflufenzopyr-sodium	Soil	1.93E-04	0.157	3.04E-05
Dimethachlor	Soil	1.09E-02	0.055	6.00E-04
Dimethenamid	Soil	5.06E-03	0.051	2.57E-04
Dimethoate	Soil	1.19E-03	0.061	7.26E-05
Dimethomorph	Soil	9.44E-03	0.036	3.41E-04
Dimethylamine	Air	6.94E-07	0.311	2.16E-07
Dimethylamine	Water	2.18E-03	0.311	6.78E-04
Dinitrogen monoxide	Air	1.17E+02	0.636	7.48E+01
Dipropylamine	Air	6.34E-04	0.138	8.77E-05
Dipropylamine	Water	1.52E-03	0.138	2.11E-04
Diquat	Soil	3.17E-03	0.152	4.81E-04
Diquat dibromide	Soil	2.94E-07	0.081	2.40E-08
Dithianone	Soil	6.59E-02	0.095	6.23E-03
Diuron	Soil	4.14E-02	0.120	4.97E-03
Epoxiconazole	Soil	1.28E-03	0.127	1.63E-04
Esfenvalerate	Air	1.15E-05	0.033	3.85E-07
Esfenvalerate	Soil	2.22E-04	0.033	7.42E-06
Ethalfluralin	Soil	3.65E-03	0.126	4.60E-04
Ethylamine	Air	1.94E-04	0.311	6.02E-05
Ethylamine	Water	4.65E-04	0.311	1.44E-04
Ethylene diamine	Air	3.76E-04	0.466	1.75E-04
Ethylene diamine	Water	9.06E-04	0.466	4.22E-04
Fenbuconazole	Soil	3.91E-08	0.166	6.50E-09
Fenoxaprop	Air	1.51E-05	0.042	6.33E-07
Fenoxaprop	Soil	5.55E-04	0.042	2.33E-05
Fenoxaprop-P ethyl ester	Soil	1.37E-07	0.039	5.32E-09
Fenpiclonil	Soil	4.32E-04	0.118	5.10E-05

Substance	**Compartment**	**Nitrogen inventory result [g]**	**Nitrogen coefficient**	**Reactive nitrogen [g]**
Fenpropidin	Soil	7.25E-03	0.051	3.71E-04
Fenpropimorph	Soil	1.43E-03	0.046	6.62E-05
Fipronil	Soil	1.59E-01	0.128	2.04E-02
Florasulam	Soil	1.05E-05	0.195	2.04E-06
Fluazifop-p-butyl	Air	2.17E-05	0.037	7.91E-07
Fluazifop-P-butyl	Soil	2.84E-03	0.037	1.04E-04
Flucarbazone sodium salt	Soil	9.62E-06	0.134	1.29E-06
Fludioxonil	Soil	2.36E-04	0.113	2.66E-05
Flufenacet	Air	8.12E-06	0.116	9.39E-07
Flufenacet	Soil	1.00E-03	0.116	1.16E-04
Flumetsulam	Air	1.90E-06	0.215	4.09E-07
Flumetsulam	Soil	3.38E-04	0.215	7.28E-05
Flumiclorac-pentyl	Air	3.25E-06	0.033	1.07E-07
Flumiclorac-pentyl	Soil	1.39E-07	0.033	4.60E-09
Flumioxazin	Air	3.29E-05	0.079	2.60E-06
Flumioxazin	Soil	2.54E-04	0.079	2.01E-05
Fluroxypyr	Soil	6.50E-03	0.110	7.14E-04
Flurtamone	Soil	1.09E-03	0.042	4.56E-05
Flusilazole	Soil	3.65E-07	0.133	4.87E-08
Folpet	Soil	1.84E-02	0.047	8.68E-04
Fomesafen	Air	1.22E-04	0.064	7.80E-06
Fomesafen	Soil	1.67E-03	0.064	1.07E-04
Foramsulfuron	Soil	3.62E-05	0.186	6.73E-06
Formamide	Air	1.68E-04	0.311	5.22E-05
Formamide	Water	4.03E-04	0.311	1.25E-04
Glyphosate	Air	2.44E-02	0.083	2.02E-03
Glyphosate	Soil	1.24E+00	0.083	1.02E-01
Imazamox	Air	4.86E-06	0.138	6.69E-07
Imazamox	Soil	2.77E-04	0.138	3.81E-05
Imazapyr	Soil	4.83E-06	0.161	7.76E-07
Imazaquin	Air	1.55E-05	0.135	2.09E-06
Imazaquin	Soil	6.64E-07	0.135	8.96E-08
Imazethapyr	Air	3.21E-05	0.145	4.66E-06
Imazethapyr	Soil	5.63E-04	0.145	8.18E-05
Imidacloprid	Soil	1.57E-01	0.274	4.29E-02
Ioxynil	Soil	2.29E-02	0.038	8.64E-04
Iprodione	Soil	6.22E-03	0.127	7.92E-04
Isocyanic acid	Air	8.06E-03	0.326	2.63E-03
Isopropylamine	Air	1.24E-04	0.237	2.94E-05
Isopropylamine	Water	2.98E-04	0.237	7.07E-05
Isoproturon	Soil	8.13E-03	0.136	1.10E-03
Isoxaflutole	Soil	5.79E-04	0.039	2.26E-05
Kresoxim-methyl	Soil	3.56E-04	0.045	1.59E-05
Lactofen	Air	1.56E-05	0.030	4.73E-07
Lactofen	Soil	6.69E-07	0.030	2.03E-08
Lambda-cyhalothrin	Soil	2.96E-03	0.031	9.21E-05
Linuron	Soil	1.09E-02	0.112	1.23E-03
Mancozeb	Soil	3.71E-01	0.104	3.85E-02

Substance	**Compartment**	**Nitrogen inventory result [g]**	**Nitrogen coefficient**	**Reactive nitrogen [g]**
Mefenpyr	Soil	5.61E-04	0.088	4.96E-05
Mefenpyr-diethyl	Soil	2.75E-07	0.075	2.06E-08
Mepiquat chloride	Soil	3.78E-03	0.094	3.54E-04
Mesotrione	Soil	1.57E-03	0.041	6.48E-05
Metamitron	Soil	9.83E-04	0.277	2.72E-04
Metazachlor	Soil	2.58E-02	0.151	3.91E-03
Methylamine	Air	1.41E-04	0.451	6.37E-05
Methylamine	Water	3.39E-04	0.451	1.53E-04
Metolachlor	Air	2.55E-04	0.049	1.26E-05
Metolachlor	Soil	1.37E-01	0.049	6.75E-03
Metribuzin	Air	1.01E-04	0.261	2.65E-05
Metribuzin	Soil	9.51E-03	0.261	2.49E-03
Monocrotophos	Soil	1.77E-02	0.063	1.11E-03
Monoethanolamine	Air	1.72E-02	0.229	3.93E-03
Monoethanolamine	Water	4.12E-06	0.229	9.44E-07
Napropamide	Soil	1.26E-01	0.052	6.52E-03
Nitrogen	Air	9.03E-01	0.000	0.00E+00
Nitrate	Air	4.47E-03	0.226	1.01E-03
Nitrate	Water	4.34E+03	0.226	9.80E+02
Nitrate	Soil	4.38E-03	0.226	9.89E-04
Nitrite	Water	1.86E-01	0.304	5.65E-02
Nitrobenzene	Air	3.10E-03	0.114	3.53E-04
Nitrobenzene	Water	1.24E-02	0.114	1.41E-03
Nitrogen	Water	5.28E+00	1.000	5.28E+00
Nitrogen	Soil	4.14E-04	1.000	4.14E-04
Nitrogen fluoride	Air	1.31E-07	0.197	2.59E-08
Nitrogen oxides	Air	4.20E+02	0.304	1.28E+02
Nitrogen, organic bound	Water	1.29E+01	0.160	2.06E+00
Nitrogen, total	Water	2.09E+00	1.000	2.09E+00
Orbencarb	Soil	2.27E-03	0.054	1.23E-04
Parathion	Soil	8.62E-02	0.048	4.14E-03
Particulates, < 10 μm (mobile)	Air	5.31E-01	0.054	2.88E-02
Particulates, < 10 μm (stationary)	Air	9.02E-01	0.054	4.89E-02
Particulates, < 2.5 μm	Air	8.71E+01	0.081	7.02E+00
Particulates, > 2.5 μm, and < 10μm	Air	3.79E+01	0.028	1.06E+00
Pendimethalin	Air	6.86E-04	0.149	1.02E-04
Pendimethalin	Soil	9.28E-02	0.149	1.39E-02
Phenmedipham	Soil	1.80E-04	0.093	1.68E-05
Pronamide	Soil	1.19E-09	0.055	6.48E-11
Propanil	Soil	2.78E-01	0.064	1.79E-02
Propiconazole	Air	1.20E-05	0.123	1.47E-06
Propiconazole	Soil	5.48E-03	0.123	6.73E-04
Propylamine	Air	1.29E-04	0.237	3.05E-05
Propylamine	Water	3.09E-04	0.237	7.33E-05
Simazine	Soil	2.44E-03	0.347	8.47E-04
Sulfentrazone	Air	7.79E-05	0.145	1.13E-05
Sulfentrazone	Soil	2.63E-03	0.145	3.80E-04
t-Butylamine	Air	8.76E-05	0.192	1.68E-05

Substance	Compartment	Nitrogen inventory result [g]	Nitrogen coefficient	Reactive nitrogen [g]
t-Butylamine	Water	2.10E-04	0.192	4.02E-05
Tebupirimphos	Soil	1.01E-03	0.088	8.92E-05
Tebutam	Soil	4.82E-01	0.060	2.89E-02
Tralkoxydim	Soil	7.20E-05	0.043	3.06E-06
Trifloxystrobin	Air	7.10E-07	0.069	4.87E-08
Trifloxystrobin	Soil	1.83E-02	0.069	1.26E-03
Trifluralin	Air	1.12E-03	0.125	1.41E-04
Trifluralin	Soil	1.89E-01	0.125	2.37E-02
Trimethylamine	Air	3.71E-05	0.237	8.78E-06
Trimethylamine	Water	8.89E-05	0.237	2.11E-05
Urea	Water	1.75E-04	0.466	8.15E-05
Total product system	-	-	-	**1.48E+03**

Also for this application, examining these first results, considerations may be made regarding the substances that make the greatest contribution in terms of reactive nitrogen for the reference product system analyzed. Specifically, nitrate emissions to water make the greatest contribution (66.3 %) followed in the ranking by ammonia emissions to air (18.4 %), nitrogen oxides to air (8.7 %), dinitrogen monoxide to air (5.1 %), particulates < 2.5 μm to air (0.5 %) and ammonium ion to water (0.3 %).

Compared to the results obtained in the previous agri-food products application, it is noted that the nitrate emissions contribution is lower, while is higher the relative contribution of other substances, with particular reference to particulate emissions: this results is justified by the inclusion of non-agricultural products and processes in the product system.

4.2.4 Reference product system: characterization

Starting from the nitrogen inventory results, the next step of the methodology involves the calculation of nitrogen impact assessment profile, consisting of the union of the category indicator results for the nine selected impact categories, obtained by applying the characterization factors to the detected emissions of nitrogen-containing substances. The results of the calculation of nitrogen impact assessment profile for the reference product system are reported in the Table 4.11 where the nitrogen-containing substances, for which characterization factors are defined by the models used, are listed for each impact category. For simplicity of calculation a cut-off criterion was applied, limited to the impact categories freshwater ecotoxicity, human toxicity cancer effect and human toxicity non-cancer effect, excluding the substances which make a contribution of less than 0.1% to the total impact of each category.

Table 4.11. *Nitrogen impact assessment profile calculated for the reference product system. Cut-off criterion of 0.1% applied for the categories Freshwater ecotoxicity, Human toxicity cancer effect and Human toxicity non-cancer effect.*

Category	Substance	Compart.	Unit	Category results
Climate change	Dinitrogen monoxide	Air	kg CO_2 eq	3.11E+01
Climate change	Nitrogen fluoride	Air	kg CO_2 eq	2.11E-06
Climate change	**Total**		**kg CO_2 eq**	**3.11E+01**
Particulate matter	Ammonia	Air	kg $PM_{2.5}$ eq	2.20E-02
Particulate matter	Nitrogen oxides	Air	kg $PM_{2.5}$ eq	3.09E-03
Particulate matter	Particulates, < 10 µm (mobile)	Air	kg $PM_{2.5}$ eq	1.21E-04
Particulate matter	Particulates, < 10 µm (stationary)	Air	kg $PM_{2.5}$ eq	2.06E-04
Particulate matter	Particulates, < 2.5 µm	Air	kg $PM_{2.5}$ eq	8.82E-02
Particulate matter	**Total**		**kg $PM_{2.5}$ eq**	**1.14E-01**
Photochemical ozone formation	Nitrogen oxides	Air	kg NMVOC eq	4.20E-01
Photochemical ozone formation	**Total**		**kg NMVOC eq**	**4.20E-01**
Acidification	Ammonia	Air	molc H^+ eq	9.96E-01
Acidification	Nitrogen oxides	Air	molc H^+ eq	3.11E-01
Acidification	**Total**		**molc H^+ eq**	**1.31E+00**
Terrestrial eutrophication	Ammonia	Air	molc N eq	4.45E+00
Terrestrial eutrophication	Nitrate	Air	molc N eq	1.41E-05
Terrestrial eutrophication	Nitrogen oxides	Air	molc N eq	1.79E+00
Terrestrial eutrophication	**Total**		**molc N eq**	**6.24E+00**
Marine eutrophication	Ammonia	Air	kg N eq	3.03E-02
Marine eutrophication	Ammonium, ion	Water	kg N eq	3.99E-03
Marine eutrophication	Nitrate	Air	kg N eq	1.25E-07
Marine eutrophication	Nitrate	Water	kg N eq	9.81E-01
Marine eutrophication	Nitrite	Water	kg N eq	5.65E-05
Marine eutrophication	Nitrogen oxides	Air	kg N eq	1.63E-01
Marine eutrophication	Nitrogen, total	Water	kg N eq	2.09E-03
Marine eutrophication	**Total**		**kg N eq**	**1.18E+00**
Freshwater ecotoxicity	Aldicarb	Soil	CTUe	5.84E+00
Freshwater ecotoxicity	Chlorpyrifos	Soil	CTUe	4.24E+01
Freshwater ecotoxicity	Diflubenzuron	Soil	CTUe	2.46E+01
Freshwater ecotoxicity	Fipronil	Soil	CTUe	5.14E+00
Freshwater ecotoxicity	Folpet	Soil	CTUe	7.00E+00
Freshwater ecotoxicity	Parathion	Soil	CTUe	7.16E+00
Freshwater ecotoxicity	Propanil	Soil	CTUe	1.68E+01

Category	Substance	Compart.	Unit	Category results
Freshwater ecotoxicity	**Total**		**CTUe**	**1.09E+02**
Human toxicity, cancer effects	**Total**		**CTUh**	**0.00E+00**
Human toxicity, non-cancer effects	**Total**		**CTUh**	**0.00E+00**

Applying the cut-off criterion described above, were not found nitrogen-containing substances assigned to the impact categories human toxicity cancer effect and human toxicity non-cancer effect, for which emissions of toxic substances, even nitrogen-containing, can be detected in extremely low amounts.

Analyzing the output format of the results obtained from the characterization, it is evident that the profile provides information on the nature of the potential environmental impacts and on their scale. In this sense, the information provided is much more complete than that presented by the reactive nitrogen indicator previously calculated, only showing general indications of the potential overall impact of the analyzed system.

4.2.5 Reference product system: normalization and weighting

In the final step of the methodology are provided the normalization and weighting procedures: in particular, for this application, the main objective is to calculate the weighting factors, starting from inventory and characterizations results and applying the proposed internal method.

Despite being outside of the initial objectives of this application, it was also calculated the normalized nitrogen assessment profile for the reference product system, obtaining the results reported in the Table 4.12. The normalized category results were calculated by applying the reference normalization factors selected for the methodology, as illustrated in the previous chapter devoted to the methodology description.

Table 4.12. *Results of normalized impact assessment profile calculated for the reference product system. Normalization factors extracted from Benini et al. (2014).*

Category	Category results	Normalization factors	Normalized category results
Climate change	3.11E+01 kg CO_2 eq	9.22E+03	3.38E-03
Particulate matter	1.14E-01 kg $PM_{2.5}$ eq	3.80E+00	2.99E-02
Photochemical ozone formation	4.20E-01 kg NMVOC eq	3.17E+01	1.33E-02
Acidification	1.31E+00 molc H^+ eq	4.73E+01	2.76E-02

Category	Category results	Normalization factors	Normalized category results
Terrestrial eutrophication	6.24E+00 molc N eq	1.76E+02	3.55E-02
Marine eutrophication	1.18E+00 kg N eq	1.69E+01	6.99E-02
Freshwater ecotoxicity	1.09E+02 CTUe	8.74E+03	1.25E-02
Human toxicity, cancer effects	0.00E+00 CTUh	3.69E-05	0.00E+00
Human toxicity, non-cancer effects	0.00E+00 CTUh	5.33E-04	0.00E+00

As anticipated in the previous chapter, compared to the results of nitrogen impact assessment profile, reported in the Table 4.11, the normalized results allow a greater comprehensibility and a direct comparison between the impact categories results, as the indicator results are expressed in the same unit of measure. For the analyzed reference product system, the normalized profile showed the greatest impact in the category marine eutrophication, to which are associated for example the nitrate emissions to water, followed in the ranking by the categories terrestrial eutrophication, due to ammonia emissions to air and particulate matter, due to particulates < 2.5 μm emissions to air.

For the subsequent calculation of the weighting factors, the proposed methodology provides to implement a specifically designed procedure that only uses internal data, generated within the previous step of the methodology, thus excluding the contribution of factors from external sources. In particular, the operational procedure provides to use the results of nitrogen inventory and characterization steps in order to calculate the category reactive nitrogen and then the category weighting factors. The outcome of the calculation is reported in the Table 4.13, showing also the main substances contribution to the category reactive nitrogen. Being the results derived from the outputs of the characterization, also in this case is valid a cut-off criterion of 0.1% of total category impact, limited to the impact categories freshwater ecotoxicity, human toxicity cancer effect and human toxicity non-cancer effect.

Table 4.13. *Weighting factors calculation results for the reference product system obtained by applying the internal weighting method provided by the proposed methodology.*

Category	Substance	Compart.	Reactive nitrogen results [kg]	Weighting factors [%]
Climate change	Dinitrogen monoxide	Air	3.11E+01	
Climate change	Nitrogen fluoride	Air	2.11E-06	
Climate change	**Total**		**3.11E+01**	**2.675%**
Particulate matter	Ammonia	Air	2.20E-02	
Particulate matter	Nitrogen oxides	Air	3.09E-03	
Particulate matter	Particulates, < 10 μm (mobile)	Air	1.21E-04	

Category	**Substance**	**Compart.**	**Reactive nitrogen results [kg]**	**Weighting factors [%]**
Particulate matter	Particulates, < 10 µm (stationary)	Air	2.06E-04	
Particulate matter	Particulates, < 2.5 µm	Air	8.82E-02	
Particulate matter	**Total**		**1.14E-01**	**14.544%**
Photochemical ozone formation	Nitrogen oxides	Air	4.20E-01	
Photochemical ozone formation	**Total**		**4.20E-01**	**4.578%**
Acidification	Ammonia	Air	9.96E-01	
Acidification	Nitrogen oxides	Air	3.11E-01	
Acidification	**Total**		**1.31E+00**	**14.290%**
Terrestrial eutrophication	Ammonia	Air	4.45E+00	
Terrestrial eutrophication	Nitrate	Air	1.41E-05	
Terrestrial eutrophication	Nitrogen oxides	Air	1.79E+00	
Terrestrial eutrophication	**Total**		**6.24E+00**	**14.290%**
Marine eutrophication	Ammonia	Air	3.03E-02	
Marine eutrophication	Ammonium, ion	Water	3.99E-03	
Marine eutrophication	Nitrate	Air	1.25E-07	
Marine eutrophication	Nitrate	Water	9.81E-01	
Marine eutrophication	Nitrite	Water	5.65E-05	
Marine eutrophication	Nitrogen oxides	Air	1.63E-01	
Marine eutrophication	Nitrogen, total	Water	2.09E-03	
Marine eutrophication	**Total**		**1.18E+00**	**49.608%**
Freshwater ecotoxicity	Aldicarb	Soil	5.84E+00	
Freshwater ecotoxicity	Chlorpyrifos	Soil	4.24E+01	
Freshwater ecotoxicity	Diflubenzuron	Soil	2.46E+01	
Freshwater ecotoxicity	Fipronil	Soil	5.14E+00	
Freshwater ecotoxicity	Folpet	Soil	7.00E+00	
Freshwater ecotoxicity	Parathion	Soil	7.16E+00	
Freshwater ecotoxicity	Propanil	Soil	1.68E+01	
Freshwater ecotoxicity	**Total**		**1.09E+02**	**0.010%**
Human toxicity, cancer effects	**Total**		**0.00E+00**	**0.005%**
Human toxicity, non-cancer effects	**Total**		**0.00E+00**	**0.005%**
	Total		**2.79E+00**	**100.000%**

Although theoretically it was achieved a result equal to 0, following the application of the cut-off criterion for the impact categories human toxicity cancer effect and human toxicity non-cancer effect, to these categories was however attributed a result equal to 0.005%, corresponding to half the calculated result for the category freshwater ecotoxicity. This choice was made in order not to exclude a priori the applicability of the reference set thus calculated to these impact categories.

Despite being, also in this case, outside of the initial objectives of this application, it was also calculated the weighted nitrogen assessment profile for the reference product system and the single score nitrogen impact indicator, obtaining the results reported in the Table 4.14. Specifically, the calculated weighting factors were applied to the normalized category results obtaining the corresponding weighted category results: finally, the impact indicator result was calculated as the summation of the weighted category results for the considered impact categories.

Table 4.14. *Weighted nitrogen assessment profile (last column) and single score nitrogen impact indicator results (last row) calculated for the reference product system.*

Category	Normalized category results	Weighting factors	Weighted category results
Climate change	3.38E-03	2.675%	9.03E-05
Particulate matter	2.99E-02	14.544%	4.35E-03
Photochemical ozone formation	1.33E-02	4.578%	6.07E-04
Acidification	2.76E-02	14.290%	3.95E-03
Terrestrial eutrophication	3.55E-02	14.290%	5.07E-03
Marine eutrophication	6.99E-02	49.608%	3.47E-02
Freshwater ecotoxicity	1.25E-02	0.010%	1.25E-06
Human toxicity, cancer effects	0.00E+00	0.005%	0.00E+00
Human toxicity, non-cancer effects	0.00E+00	0.005%	0.00E+00
Total (single score nitrogen impact indicator)			**4.87E-02**

The effect of weighting procedure on the impact profile, respect to the normalized results, was a further increase of the relative importance of the impact category marine eutrophication, to which a high factor is associated due to nitrate emissions: On the other side was found a decrease of the relative impact of the categories to which low weighting factors are associated, such as climate change and freshwater ecotoxicity. The results are congruent with the intentions of the weighting method, designed to amplify the relative importance of the impact categories associated with higher emissions in terms of reactive nitrogen.

4.2.6 Reference product system: interpretation of the results

In addition to what has been highlighted in the preceding paragraphs with the presentation of the results obtained, the following is to be noted in relation to the objectives set for the application:

- All the operative steps of the proposed methodology were successfully applied to a specifically created product system allowing the calculation of nitrogen inventory results, reactive nitrogen indicator, nitrogen impact assessment profile and single score nitrogen impact indicator, after determining the internal weighting factors.

- The application allowed in particular calculating the weighting factors related to the reference system using the specific weighting method defined as part of the proposed methodology. The weighting set thus obtained can be used as an alternative reference for subsequent applications in substitution or complementary to the set obtained through the procedure provided by the methodology or to other external weighing sets not specifically designed for nitrogen impact accounting.

  As for the results obtained for the weighting factors, as expected, a high value resulted for the impact categories to which are associated the greatest amount of reactive nitrogen, first of all for the category marine eutrophication (49.6 %), followed by particulate matter (14.5 %), acidification and terrestrial eutrophication (14.3 %). For the impact categories that have low relevance respect to the environmental impacts associated with the nitrogen cycle, low weighting factor were obtained, as in the case of climate change (2.7 %), freshwater ecotoxicity (0.01 %), human toxicity cancer effect and human toxicity non-cancer effect (0.005 %). These results must be taken into account when using this reference set in applications requiring a particular enhancement of these impact categories, according to the goal and scope of the specific application.

4.3 Methodology application to agricultural processes

After database-based applications described in the previous paragraphs, a first experimentation was carried out, using real data collected on the field, related to the comparison of two cultivation methods (traditional and organic) for the production of barley. This specific application is described in the following paragraphs.

4.3.1 Agricultural processes: goal and scope definition

This application consists in the comparative assessment, referred to nitrogen-related impacts, between a conventional and an organic barley crop production. The main objectives of the study can be synthetized as follows:

- to test the application of the whole methodology on a comparative case based on real data;

- to evaluate and compare the potential environmental impacts related to the nitrogen cycle of barley crops cultivated with two alternative farming system: conventional and organic.

For this application, an original model designed by Fedele *et al.* (2010) has been used as a reference and updated with modified model designed by Candian *et al.* (2014) and subsequent data and information taken from Guariento *et al.* (2016).

The ***product systems*** are represented by the agricultural processes performed during the cultivation of the barley necessary for the cultivation of the agricultural product for both the alternatives, including all the related auxiliary processes such as the transport associated with the provision of seeds and fertilizers or maintenance of farm machinery.

The ***systems function*** is the production of 1 kg of seed referred to an annual barley agricultural production.

The ***functional unit*** assumed as reference is defined as "1kg of barley seed product referred to a one year production cycle" for both conventional and organic cultivations.

The ***system boundaries*** were defined following a common farming practices (starting from ploughing to harvesting) which have been used to characterized an appropriate "data collection". These data were used as a guideline for the definition of the system boundaries for both the conventional and the organic cultivation systems. All field processes for the cultivation of the conventional and organic barley were included within the system boundaries, by referring to an assumed cultivated area of one hectare. The specific yield of the relative crop was used to convert all processes data and quantities referred to this area in the functional unit of 1kg of finished product.

Was considered a distance of 20 km between the farm and the consortium for the purchase of fertilizers and other products and between the farm and the seeds supply point (this scenario reflects a suitable situation in the northern Italy). Moreover, it was assumed that the farm and the storage equipment were adjacent to the field, so the distance to reach the field with the machineries was considered negligible and omitted from the scope. For each phase of the cultivation, all the input and output flows of mass and energy were considered. In this application, capital goods were not considered since not relevant for the comparison being very similar for the two analyzed systems. In addition, the maintenance of machinery and equipment operations such as greasing, oil and filter change were not considered.

In the analyzed case, barley straws were ploughed and interred into the soil after the harvest so they were considered as new organic matter that bring nutritive substances to the soil. This organic matter was also considered in the application of the soil emissions models and in the calculated amount of fertilizers to use: in fact, the amount of fertilizer to use was considered variable depending on the contribution given by such crop residues.

Models for the calculation of field emissions described in Candian *et al.* (2014) were used because of the difficulty to measure the data regarding direct field emissions.

Allocation criteria were not adopted since in the systems under consideration are not considered co-products.

A ***cut-off criterion*** was applied in order to choose flows to be included within the system boundaries: specifically, a mass cut-off criterion of 1% with respect to the total sum of material: so all processes and fluxes contributing less than this percentage were excluded from the system. Despite this choice, herbicides and pesticides used in the conventional agriculture system were considered. Regarding this assumption was adopted also the environmental importance criterion, so even if their quantities were inferior to 1% by mass, they have been considered in the computation. This is important because the use of herbicides and pesticides represents one of the most significant differences between conventional and the organic system.

The ***requirements for data quality*** were defined giving priority, when available, to the use of primary data (as for example for the diesel consumed by farm machinery during the farming processes). Other data were derived with empirical models, such as the IPCC model (De Klein *et al.*, 2006), Ecoinvent model (Nemecek *et al.*, 2016) and EMEP/EEA model (Winther *et al.*, 2010), for the estimation of the emissions compound connected with soil use. Finally, other data were selected from databases, using Ecoinvent 3.0 database as primary choice.

Data time coverage original data referred to the year 2009, representing a year in which the climatic conditions have been in line with the seasonal average, were subsequently partially updated to the year 2015. ***Data spatial coverage*** refers to a farm located in the Polesine area in the Northern part of Italy.

The ***temporal system boundary*** for both crops studied is considered a "one year crop cycle" starting just after the harvest of the previous barley production and ending with the harvest inherent to the case study considered.

The application has a "cradle to gate" approach: all subsequent stages after harvesting as processing and transportation, sale, utilization and end of life phases were omitted.

With regard to the agricultural activities for barley cultivation used as a reference for the model, the same are presented in the Table 4.15 for both the alternatives with reference to an annual standard cultivation cycle.

Table 4.15. *Steps of barley production for conventional and organic system. Source: Fedele et al. (2010).*

Period of practice application	Conventional agriculture	Organic agriculture
End of September	Ploughing	Ploughing
Beginning of October	Roughing harrowing	Roughing harrowing
Beginning of October	Mineral fertilization	Organic fertilization
End of October	Sowing	Sowing
Beginning of November	Weeds treatments	-
End of February/ beginning of March	Post-seeding fertilization	Post-seeding fertilization
March/April	Plant protection treatment	-
June	Harvesting	Harvesting

The above presented agricultural activities are sinthetically described below:

- ***Ploughing.*** It is the first phase of land preparation. It is done in autumn, usually at the end of September. It consists in the rotation of terrain, performed through a plow with the aim of: aerate soil to improve the activity of aerobic microorganisms; increase the porosity of the soil, making it more permeable. In this way water infiltration is easier and runoff and shallow backwater phenomena in case of extreme events are avoided; inhibit the action of some infesting plants; simplify the successive operations, breaking the soil and making it more compact.
- ***Harrowing.*** It consists in the preparation of seedbed before burying the seed and which can be conducted with various types of harrows. This operation acts in the superficial part of the soil (10-15 cm) where the dimensions of clumps are reduced and surface is levelled. This type of harrowing is defined as "roughing harrowing" when done after the ploughing phase, otherwise it is called "finishing harrowing" if done after a fertilization, acting burying the spread fertilizers. Other functions are: undergrounding of volatile herbicides, incorporating into the soil to prevent evaporation; burying of seeds and fertilizers; breaking of soil's crust; elimination of possible emergency weeds.
- ***Fertilization.*** This technique allows providing an adequate supply of nutrients to the soils according to the type of cultivation carried out. It can be performed in different moment of the cultivation cycle: for this reason can assume different names: "base fertilization", "pre-seeding fertilization", "post-seeding fertilization". The base fertilization is generally done between the roughing and finishing harrowing, the pre-seeding fertilization is realized a little bit before or during the seeds burial (after finishing harrowing). Pre-seeding fertilization refers to the fertilizers contribution to the soil to increase the rate of plant growth and production. All of them are characteristics of the conventional barley cultivation, while for the organic barley cultivation only base fertilization and post-seeding fertilization is applied. Different type of fertilizers can be used,

but the main classification consists in the subdivision of organic and chemicals categories. The first is usually applied in the conventional procedure: in this application triple superphosphate (P_2O_5) is used for barley conventional system. The second one, typically organic compost, is used within organic procedure.

- ***Sowing.*** Consists in the distribution of seeds in the soil. The success of this step depends on the amount of the seeds used, the right soil preparation and the correct depth of the sowing (not neglecting humidity and optimal value of temperature).
- ***Weeds treatment.*** Practice adopted in the conventional agriculture for the elimination of the weeds (infesting plants) that require the application of very selective chemicals herbicides not harmful for the crop. The choice of a “pre-emergence” (in autumn) instead of a “post-emergence” (in spring) treatment is related to the type of substances to be eliminated and their sensibility to the geo-climate conditions in the zone of actions.
- ***Plant protection treatment.*** This step is most of time necessary to protect the plant and eliminate parasites dangerous for their growth. The choice of the treatment mainly depends on the type of cultivation and the species of parasites. Some common pesticides are acaricides, fungicides and insecticides.
- ***Harvesting.*** Final phase of the cultivation cycle, performed during the summer periods. It is generally done using an harvester that simultaneously realizes harvesting and threshing, extracting the cereal grains from their husks, from the stems, the spikes and separating them from the organic part (called straw).

In the flow diagrams reported below (Figures 4.2 and 4.3) are illustrated the two system boundaries considered, in which are represented the flows and the unit processes related to an annual cultivation crop of conventional barley and organic barley.

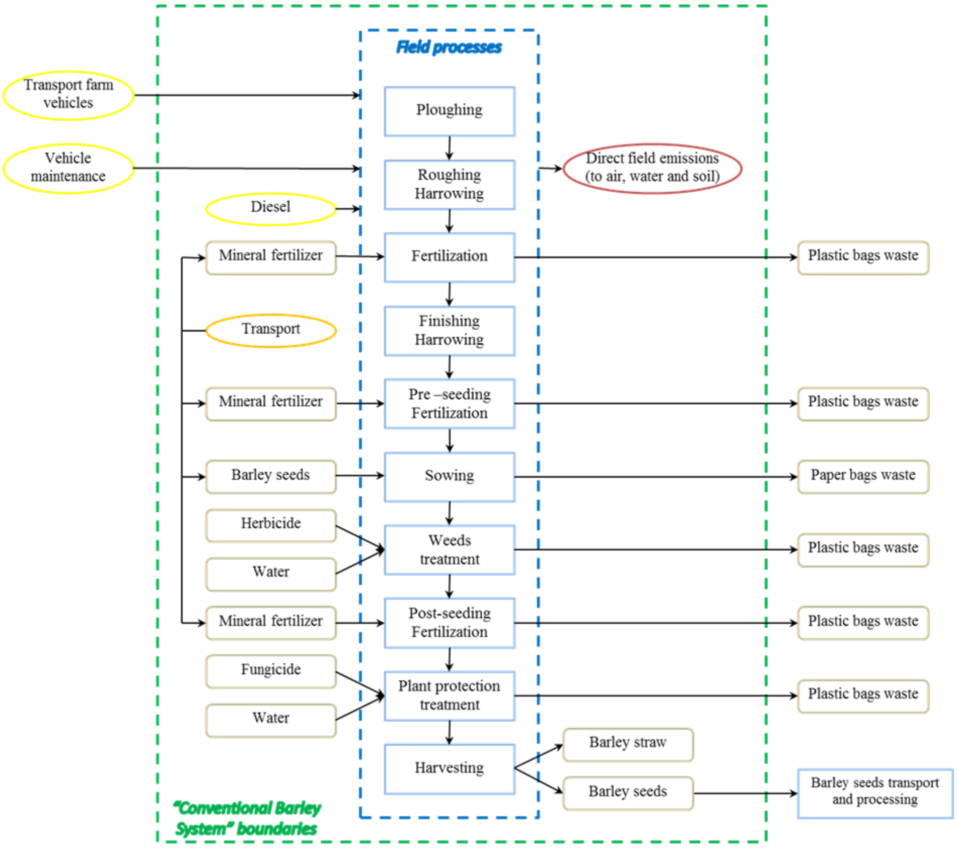


Figure 4.2. *System boundaries schematic representation for the conventional barley cultivation. Source: Candian et al. (2014)*

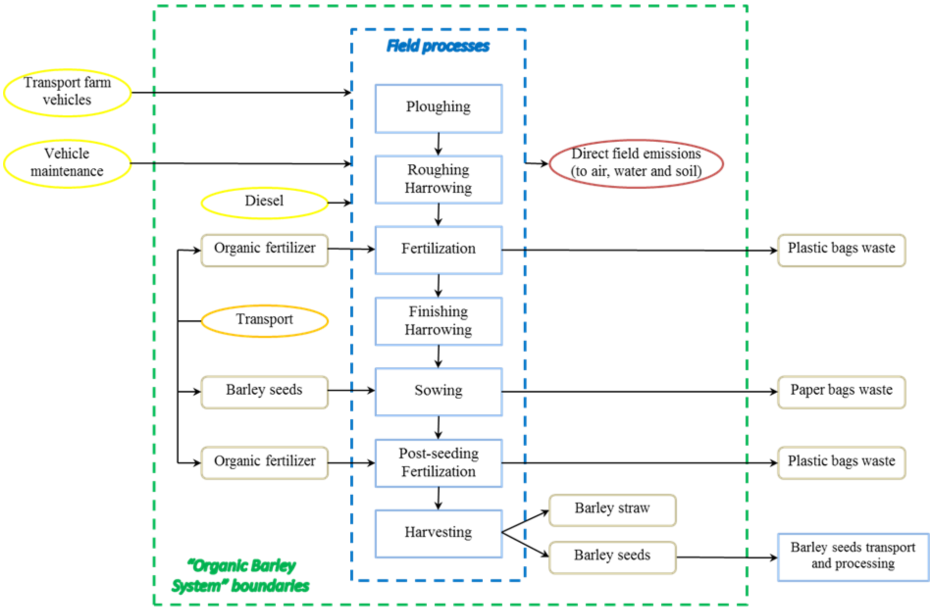


Figure 4.3. *System boundaries schematic representation for the organic barley cultivation. Source: Candian et al. (2014)*

In the above reported diagrams, the green dashed line represents the system boundaries of the conventional barley and organic barley cultivation, respectively. Fluxes outside the green dashed line are excluded from the system boundaries and not taken into account. The blue dashed line includes all the field processes considered.

4.3.2 Agricultural processes: inventory analysis

Regarding the data used for the inventory analysis step of the application, they were collected relatively to each stage of production. Primary data were gathered directly from the farmers, concerning all the field processes referred to 1 ha of cultivated land (diesel consumption, mineral and organic fertilizers use, pesticides use, seed production etc.). All these primary data are summarized in the Table 4.16 for both the product systems.

Table 4.16. *Agricultural primary inventory data (referred to 1 ha of crop land) for the conventional and organic barley product systems.*

Input data	Unit	Barley Conventional	Barley Organic
Fertilizer triple superphosphate (46% P_2O_5)	kg	450	-
Fertilizer urea (46%N)	kg	200	-
Fertilizer organic compost	kg	-	350
Herbicide “Combi Fluid”	k	1.5	-
Fungicide “Faro”	l	1.5	-
Seeds	kg	180	180
Crop yield	kg	7000	5500
Diesel fuel (total consumption)	kg	86.43	80.47

All emissions from soil use have been calculated by means empirical models above described, starting from primary data. For all other included data, Ecoinvent 3.0 database was used.

In the case of compounds like herbicides, pesticides, fertilizers for which there are no co-respective compounds in the database, these were modeled starting from basic substances.

A summary of the data used for the agricultural processes considered is provided below:

- ***Ploughing and harrowing.*** The only input considered in these operations is the diesel fuel consumed by the tractor. This input was taken from Ecoinvent database and includes the transportation of product from the refinery to the end user, the operation of storage tanks and the emissions from evaporation and treatment of effluents. All emissions to air generated by diesel combustion were accounted using the model presented in the EMEP/EEA guidebook (Winther *et al.*, 2010) and developed within "CORINAIR".

- ***Fertilization.*** In this activity are considered the following items:
  - diesel fuel consumption (for both systems),
  - triple superphosphate (P_2O_5) used as fertilizer (only for conventional system), taken from Ecoinvent database considering all processes that concern its production, the transports of raw materials and of the fertilizer product from the factory to the regional department store, production and waste treatment are also taken into account;
  - transport of 300 kg of fertilizer used over a distance of 20 km, using Ecoinvent database and considering all the operation, production, maintenance and disposal of the vehicle, and the construction, maintenance and disposal of the road (only for conventional system);
  - organic compost used as fertilizer (only for organic system), taken from Ecoinvent database considering process emissions, infrastructure and energy demand for operating a compost plant as well as transports related to the collection of the biogenic waste;
  - transport by lorry to carry the 150 kg of organic fertilizer over a distance of 20 km (only for organic system);
  - plastic packaging for the fertilizer are not considered in this process due to the cut-off rule set;
  - output emissions, calculated using the "CORINAIR" model.
- ***Sowing.*** In this process are considered the following items:
  - Diesel fuel consumption;
  - Barley seeds used for sowing, taken from Ecoinvent database including all the processes needed for the production of the seeds, the transport to the processing center, treatments (pre-cleaning, cleaning, eventually drying, chemical dressing and bag filling), storing and transport to the regional storage center (only for conventional system);
  - transport by lorry to carry 180 kg of barley seeds over a distance of 20 km (only for conventional system);
  - organic barley seeds used for seeding, taken from Ecoinvent database including all processes needed for the production of the organic seeds, the transport to the processing center, treatments (pre-cleaning, cleaning, eventually drying, chemical dressing and bag filling), storing and transport to the regional storage center (only for organic system);
  - transport by lorry to carry the 180 kg of soybean seeds over the 20 km distance (only for organic system);
  - paper packaging for the soybean seeds are not considered in this process due to the cut-off rule.
  - output emissions calculated using the "CORINAIR" model.

- ***Weeds treatment.*** In this process, carried out only for the conventional system, are considered the following items:
  - diesel fuel consumption;
  - herbicide “Combi Fluid” specifically designed considering its composition using data derived from Ecoinvent database;
  - water for the dilution of the herbicide before the use, taken from Ecoinvent database considering the infrastructure and energy use for water treatment and transportation to the end user.
  - output emissions calculated using the "CORINAIR" model.
- ***Post-seeding fertilization.*** In this process, are considered the following items:
  - diesel fuel consumption;
  - urea used as fertilizer (only for conventional system), taken from Ecoinvent database taking into account the production of urea from ammonia and carbon dioxide, the transports of the intermediate products and of the fertilizer product from the factory to the regional storehouse.
  - transport by lorry to carry the 200 kg of urea fertilizer used over a distance of 20km (only for conventional system);
  - organic compost used as fertilizer (only for organic system), taken from Ecoinvent database considering process emissions, infrastructure and energy demand for operating a compost plant as well as transports related to the collection of the biogenic waste;
  - transport by lorry to carry the 250 kg of organic fertilizer over a distance of 20 km (only for organic system);
  - plastic packaging for the fertilizer are not considered in this process due to the cut-off rule.
  - output emissions are calculated using the "CORINAIR" model.
- ***Plant protection treatment.*** In this process, , carried out only for the conventional system, are considered the following items:
  - diesel fuel consumption;
  - fungicide “Faro” specifically designed considering the sum of the active ingredient present: a benzimidazole-compound taken from the Ecoinvent database considering the processes related to its production including materials, energy uses, infrastructure and emissions;
  - water for fungicide dilution before the use;
  - output emissions are calculated using the "CORINAIR" model;

- ***Harvesting.*** The only input considered in this activity is diesel fuel consumption whilst it considers as outputs the emissions calculated with the "CORINAIR" model.

Once completed the product system design, the complete inventory was calculated and subsequently were obtained the nitrogen inventory results reported in the Table 4.17.

Table 4.17. *Nitrogen inventory results: comparison of agricultural processes for the production of 1 kg of conventional and organic barley.*

Substance	Compart.	U.o.m.	Inventory results	
			Barley conventional	**Barley organic**
2-Aminopropanol	Air	pg	281.68333	3.9071333
2-Aminopropanol	Water	pg	677.81033	9.3923463
2-Nitrobenzoic acid	Air	pg	506.09691	6.8110618
Acephate	Air	pg	588.4113	32.534671
Acephate	Soil	ng	3.9682122	0.3120503
Acetamide	Air	pg	144.84674	8.008923
Acetamide	Soil	pg	697.95211	43.893459
Acetochlor	Soil	ng	8.3201027	0.0081748
Acetonitrile	Air	µg	9.6164253	0.0105849
Acetonitrile	Water	ng	33.183519	0.0082557
Acifluorfen	Air	pg	80.773759	4.4661746
Acifluorfen	Soil	pg	3.4623853	0.1914436
Alachlor	Air	pg	571.61913	31.606191
Alachlor	Soil	ng	1.506306	0.0288498
Aldicarb	Soil	ng	13.266718	1.045242
Amidosulfuron	Soil	pg	5.272288	0.2787895
Ammonia	Air	g	2.5051169	0.3583925
Ammonium carbonate	Air	ng	23.355006	0.7095796
Ammonium, ion	Water	mg	14.330206	0.0971978
Aniline	Air	ng	15.802544	0.0308513
Aniline	Water	ng	37.939649	0.0741411
Anthranilic acid	Air	pg	393.03033	5.2961745
Asulam	Soil	pg	3.2542231	0.0027472
Atrazine	Air	pg	452.132	24.999461
Atrazine	Soil	µg	1.0334333	0.029419
Azoxystrobin	Air	pg	267.30391	14.779874
Azoxystrobin	Soil	ng	80.231917	0.0229064
Benomyl	Soil	ng	49.820522	0.0264088
Bentazone	Air	pg	247.08477	13.661909
Bentazone	Soil	pg	160.77006	8.5268098
Benzene, 1-methyl-2-nitro-	Air	pg	437.02349	5.8814699
Bifenox	Soil	ng	12.990096	1.978E-07
Bitertanol	Soil	ng	5.4774792	3.592E-08
Bromoxynil	Soil	ng	32.696235	9.001E-05
Bromuconazole	Soil	pg	0.0001484	8.039E-06
Carbaryl	Air	pg	67.477103	3.7309707
Carbaryl	Soil	pg	53.908952	0.9074855

Substance	Compart.	U.o.m.	Inventory results Barley conventional	 Barley organic
Carbendazim	Soil	ng	176.15263	0.2076432
Carbetamide	Soil	ng	179.97995	2.4951155
Carbofuran	Soil	µg	27.314098	0.0144805
Carfentrazone-ethyl	Air	pg	7.4148277	0.4099836
Carfentrazone-ethyl	Soil	pg	507.50998	0.0175771
Chloramine	Air	ng	46.41075	0.029947
Chloramine	Water	ng	414.15776	0.2673745
Chloridazon	Soil	pg	0.0132405	0.0007174
Chlorimuron-ethyl	Air	pg	134.90851	7.4594148
Chlorimuron-ethyl	Soil	ng	2.5117859	0.1876454
Chlormequat	Soil	ng	8.2807065	0.2182669
Chlorothalonil	Soil	µg	129.14243	0.0088442
Chlorpyrifos	Air	ng	2.6913163	0.1488093
Chlorpyrifos	Soil	ng	18.98585	1.4073982
Chlorsulfuron	Soil	pg	0.0002045	1.108E-05
Chlortoluron	Soil	µg	145.48473	8.969E-06
Choline chloride	Soil	pg	0.0281965	0.0015278
Cinidon-ethyl	Soil	pg	6.3907108	0.3379297
Clethodim	Air	pg	399.12815	22.068751
Clethodim	Soil	ng	3.5875104	0.2678363
Clodinafop-propargyl	Soil	pg	0.0030267	0.000164
Clomazone	Soil	ng	4.735867	0.0694002
Clopyralid	Soil	ng	1.2696594	0.0016171
Cloquintocet-mexyl	Soil	pg	0.0007311	3.962E-05
Cloransulam-methyl	Air	pg	70.264375	3.8850856
Cloransulam-methyl	Soil	ng	1.0781383	0.0805331
Cyanide	Air	µg	200.08404	0.6027969
Cyanide	Water	µg	101.51947	2.6710616
Cyanoacetic acid	Air	ng	39.62875	0.0098592
Cyfluthrin	Air	pg	14.08486	0.7787856
Cyfluthrin	Soil	pg	40.38255	2.617052
Cyhalothrin, gamma-	Air	pg	161.6389	8.9374022
Cyhalothrin, gamma-	Soil	pg	6.9293399	0.3831398
Cypermethrin	Air	pg	34.178346	1.8898026
Cypermethrin	Soil	µg	3.8701224	0.0022282
Cyproconazole	Soil	ng	721.65484	0.0040934
Cyprodinil	Soil	µg	3.010907	4.835E-06
Deltamethrin	Soil	ng	1.0191352	0.0030193
Dicrotophos	Soil	pg	723.90405	57.034069
Diethylamine	Air	ng	7.1189664	0.015265
Diethylamine	Water	ng	17.085807	0.0366364
Difenoconazole	Soil	pg	412.36506	6.1141091
Diflubenzuron	Air	pg	7.4148277	0.4099836
Diflubenzuron	Soil	ng	716.06211	53.405425
Diflufenican	Soil	ng	62.969724	0.012293
Diflufenzopyr-sodium	Soil	pg	26.947044	0.0264763
Dimethachlor	Soil	ng	11.565772	0.1694869
Dimethenamid	Soil	pg	952.68896	8.1117074

Substance	**Compart.**	**U.o.m.**	**Inventory results** **Barley conventional**	 **Barley organic**
Dimethoate	Soil	pg	548.32342	28.994395
Dimethylamine	Air	pg	12.238188	0.2894602
Dimethylamine	Water	ng	253.07015	0.1443272
Dinitrogen monoxide	Air	g	2.440461	2.7838786
Dipropylamine	Air	ng	4.3887529	0.0075262
Dipropylamine	Water	ng	10.533081	0.0180631
Diquat	Soil	ng	7.6797645	0.0040709
Diquat dibromide	Soil	pg	0.0005267	4.446E-07
Dithianone	Soil	pg	52.72288	2.7878948
Diuron	Soil	ng	1.1128062	0.0876744
Epoxiconazole	Soil	ng	11.263374	0.0036434
Esfenvalerate	Air	pg	84.235002	4.657555
Esfenvalerate	Soil	pg	4.6082816	0.2523923
Ethalfluralin	Soil	ng	3.8559272	0.0565054
Ethylamine	Air	ng	1.9629216	0.050388
Ethylamine	Water	ng	4.7110681	0.1209328
Ethylene diamine	Air	ng	14.895219	0.0514428
Ethylene diamine	Water	ng	36.085483	0.1240583
Fenbuconazole	Soil	pg	13.779571	0.7286399
Fenoxaprop	Air	pg	110.25715	6.0963821
Fenoxaprop	Soil	ng	2.1524219	0.1608032
Fenoxaprop-P ethyl ester	Soil	ng	3.76772	2.288E-08
Fenpiclonil	Soil	ng	12.508792	0.3480865
Fenpropidin	Soil	ng	165.68828	0.0115968
Fenpropimorph	Soil	µg	136.2125	2.487E-05
Fipronil	Soil	ng	4.3673981	0.3409482
Florasulam	Soil	ng	1.3789082	9.126E-09
Fluazifop-p-butyl	Air	pg	158.21193	8.7479167
Fluazifop-P-butyl	Soil	ng	3.5653076	0.0952262
Flucarbazone sodium salt	Soil	pg	1.278E-05	6.926E-07
Fludioxonil	Soil	ng	3.2460304	3.699E-08
Flufenacet	Air	pg	59.320907	3.279995
Flufenacet	Soil	ng	55.158872	0.0001409
Flumetsulam	Air	pg	13.879242	0.7674165
Flumetsulam	Soil	pg	47.753649	0.0792296
Flumiclorac-pentyl	Air	pg	23.748924	1.3131349
Flumiclorac-pentyl	Soil	pg	1.0175826	0.0562646
Flumioxazin	Air	pg	240.23082	13.282938
Flumioxazin	Soil	ng	1.2537411	0.0935177
Fluroxypyr	Soil	ng	2.3344112	0.0008369
Flurtamone	Soil	ng	57.596144	0.0073925
Flusilazole	Soil	ng	6.3244716	0.0025446
Fomesafen	Air	pg	893.18346	49.386253
Fomesafen	Soil	ng	8.2401548	0.6152129
Foramsulfuron	Soil	pg	5.0526407	0.0049644
Formamide	Air	ng	23.701214	0.0057126
Formamide	Water	ng	56.88377	0.0137104
Glyphosate	Air	ng	178.54531	9.8721976

Substance	Compart.	U.o.m.	Inventory results	
			Barley conventional	Barley organic
Glyphosate	Soil	µg	64.623358	0.246653
Imazamox	Air	pg	35.526289	1.9643336
Imazamox	Soil	ng	1.0785709	0.0805943
Imazapyr	Soil	pg	0.6736901	0.0006619
Imazaquin	Air	pg	113.26147	6.2624977
Imazaquin	Soil	pg	4.8537364	0.2683747
Imazethapyr	Air	pg	234.40497	12.960812
Imazethapyr	Soil	ng	2.694856	0.2010731
Imidacloprid	Soil	ng	29.797502	0.3336561
Ioxynil	Soil	ng	19.86717	0.0160958
Iprodione	Soil	ng	5.1730543	0.0758069
Isocyanic acid	Air	µg	5.5735418	0.233454
Isopropylamine	Air	pg	756.26793	18.187598
Isopropylamine	Water	ng	1.8150695	0.043651
Isoproturon	Soil	µg	351.5737	0.0001478
Isoxaflutole	Soil	pg	80.842531	0.0794304
Kresoxim-methyl	Soil	pg	579.47476	4.3298239
Lactofen	Air	pg	114.06109	6.306711
Lactofen	Soil	pg	4.8880062	0.2702696
Lambda-cyhalothrin	Soil	ng	7.2070051	0.036273
Linuron	Soil	ng	864.68206	26.068646
Mancozeb	Soil	ng	412.77099	11.486321
Mefenpyr	Soil	ng	13.46458	0.0001268
Mefenpyr-diethyl	Soil	ng	7.5356359	4.577E-08
Mepiquat chloride	Soil	ng	53.246276	0.0076926
Mesotrione	Soil	pg	218.95523	0.2151305
Metamitron	Soil	ng	1.0079075	0.0008947
Metazachlor	Soil	ng	27.290257	0.3999163
Methylamine	Air	ng	20.343471	0.0122009
Methylamine	Water	ng	48.824342	0.0292815
Metolachlor	Air	ng	1.8642734	0.1030801
Metolachlor	Soil	ng	358.49237	25.876988
Metribuzin	Air	pg	739.76929	40.903616
Metribuzin	Soil	ng	23.156827	1.0483918
Monocrotophos	Soil	ng	87.481184	6.5245323
Monoethanolamine	Air	µg	10.375824	0.1045774
Monoethanolamine	Water	ng	4.6340384	0.1096062
Napropamide	Soil	ng	131.56297	1.8343797
Nitrate	Air	µg	14.594601	0.6854942
Nitrate	Water	g	127.3845	120.5874
Nitrate	Soil	µg	16.226251	1.0744676
Nitrite	Water	µg	17.587506	0.5112223
Nitrobenzene	Air	µg	43.830851	4.592E-05
Nitrobenzene	Water	µg	175.65172	0.000184
Nitrogen	Air	µg	949.30127	3.2766607
Nitrogen	Water	mg	5.9199588	0.044782
Nitrogen	Soil	µg	2.2425797	0.5729416
Nitrogen fluoride	Air	pg	0.0036536	0.0011196

Substance	**Compart.**	**U.o.m.**	**Inventory results**	
			Barley conventional	**Barley organic**
Nitrogen oxides	Air	g	1.8548049	1.5417298
Nitrogen, organic bound	Water	mg	1.2188376	0.1993986
Orbencarb	Soil	ng	78.484672	2.18402
Parathion	Soil	pg	345.5967	83.052447
Particulates, < 10μm	Air	mg	55.171373	62.745392
Particulates, < 2.5μm	Air	mg	236.51091	62.799882
Particulates, > 2.5μm, and < 10μm	Air	mg	154.82415	1.1531014
Pendimethalin	Air	ng	5.0136618	0.2772174
Pendimethalin	Soil	μg	155.89304	0.0047668
Phenmedipham	Soil	pg	184.61722	0.1638775
Propiconazole	Air	pg	87.490627	4.8375663
Propiconazole	Soil	ng	62.184712	0.0032706
Propylamine	Air	pg	123.69099	1.9630951
Propylamine	Water	pg	296.86171	4.7114555
Simazine	Soil	pg	340.21133	0.3342684
Sulfentrazone	Air	pg	569.22025	31.473551
Sulfentrazone	Soil	ng	12.941069	0.9668798
t-Butylamine	Air	ng	28.047021	0.0239073
t-Butylamine	Water	ng	67.314062	0.0573783
Tebupirimphos	Soil	pg	141.48178	0.1390103
Tebutam	Soil	ng	501.55156	6.9531583
Tralkoxydim	Soil	ng	128.68112	7.864E-07
Trifloxystrobin	Air	pg	5.1907221	0.2870075
Trifloxystrobin	Soil	ng	7.4452455	1.239E-05
Trifluralin	Air	ng	8.1984623	0.4533126
Trifluralin	Soil	ng	164.05814	6.9903745
Trimethylamine	Air	pg	244.54623	3.3014807
Trimethylamine	Water	pg	586.91096	7.9235536
Urea	Water	ng	1.1421047	0.0160868

The nitrogen inventory results show higher values for all inventory emissions of the conventional barley alternative production, except for emissions to air of dinitrogen monoxide and particulates < 10 μm. Specifically, with regard to dinitrogen monoxide emission, these were accounted using the model derived from IPCC (Intergovernmental Panel on Climate Change) for the greenhouse gas inventories (De Klein *et al.*, 2006). This approach provides a description of the generic methodologies to be adopted for the inventory of dinitrogen monoxide (N_2O) emissions from managed soils, including indirect N_2O emissions from additions of N to land due to deposition and leaching, and emissions of carbon dioxide (CO_2) following additions of liming materials and urea-containing fertilizer. Although resulting, from the application of the model, higher N_2O emissions per hectare for the conventional cultivation (16.998 kg/yr ha compared to 15.278 kg/yr ha of the organic alternative), the lower yield of organic cultivation (5500 kg/ha compared to 7000 kg/ha of the conventional alternative) gave as a result higher emissions per functional unit (kg) for organic barley production. The same considerations apply to particulates emission, largely due to diesel consumption during the ploughing phase, which was assumed equal, per hectare, for both alternatives. These emission were accounted using the "CORINAIR” model (Winther *et al.*, 2010).

4.3.3 Agricultural processes: assessment at inventory level

Using the previously calculated nitrogen coefficients related to the nitrogen-containing substances, it was then possible to obtain the reactive nitrogen results for each emitted substance and for the two considered product systems (conventional and organic barley). Results are reported in the Table 4.18 comprising, for conventional and organic barley, both nitrogen inventory results and reactive nitrogen indicator results: the results related to the whole product systems are reported in the last row of the Table.

Table 4.18. *Nitrogen inventory results for the agricultural processes for the production of 1 kg of conventional and organic barley.*

Substance	**Comp.**	**Inventory results [g/kg]**		**Reactive nitrogen results [g/kg]**		
		Barley conventional	**Barley organic**	**N. coeff.**	**Barley conventional**	**Barley organic**
2-Aminopropanol	Air	2.82E-10	3.91E-12	0.186	5.25E-11	7.29E-13
2-Aminopropanol	Water	6.78E-10	9.39E-12	0.186	1.26E-10	1.75E-12
2-Nitrobenzoic acid	Air	5.06E-10	6.81E-12	0.084	4.24E-11	5.71E-13
Acephate	Air	5.88E-10	3.25E-11	0.076	4.50E-11	2.49E-12
Acephate	Soil	3.97E-09	3.12E-10	0.076	3.03E-10	2.39E-11
Acetamide	Air	1.45E-10	8.01E-12	0.237	3.43E-11	1.90E-12
Acetamide	Soil	6.98E-10	4.39E-11	0.237	1.65E-10	1.04E-11
Acetochlor	Soil	8.32E-09	8.17E-12	0.052	4.32E-10	4.24E-13
Acetonitrile	Air	9.62E-06	1.06E-08	0.341	3.28E-06	3.61E-09
Acetonitrile	Water	3.32E-08	8.26E-12	0.341	1.13E-08	2.82E-12
Acifluorfen	Air	8.08E-11	4.47E-12	0.039	3.13E-12	1.73E-13
Acifluorfen	Soil	3.46E-12	1.91E-13	0.039	1.34E-13	7.41E-15
Alachlor	Air	5.72E-10	3.16E-11	0.052	2.97E-11	1.64E-12
Alachlor	Soil	1.51E-09	2.88E-11	0.052	7.82E-11	1.50E-12
Aldicarb	Soil	1.33E-08	1.05E-09	0.147	1.95E-09	1.54E-10
Amidosulfuron	Soil	5.27E-12	2.79E-13	0.190	1.00E-12	5.29E-14
Ammonia	Air	2.51E+00	3.58E-01	0.822	2.06E+00	2.95E-01
Ammonium carbonate	Air	2.34E-08	7.10E-10	0.292	6.81E-09	2.07E-10
Ammonium. ion	Water	1.43E-02	9.72E-05	0.776	1.11E-02	7.55E-05
Aniline	Air	1.58E-08	3.09E-11	0.150	2.38E-09	4.64E-12
Aniline	Water	3.79E-08	7.41E-11	0.150	5.71E-09	1.12E-11
Anthranilic acid	Air	3.93E-10	5.30E-12	0.102	4.01E-11	5.41E-13
Asulam	Soil	3.25E-12	2.75E-15	0.122	3.96E-13	3.34E-16
Atrazine	Air	4.52E-10	2.50E-11	0.325	1.47E-10	8.12E-12

Substance	Comp.	Inventory results [g/kg]		Reactive nitrogen results [g/kg]		
		Barley conventional	Barley organic	N. coeff.	Barley conventional	Barley organic
Atrazine	Soil	1.03E-06	2.94E-08	0.325	3.36E-07	9.55E-09
Azoxystrobin	Air	2.67E-10	1.48E-11	0.104	2.78E-11	1.54E-12
Azoxystrobin	Soil	8.02E-08	2.29E-11	0.104	8.36E-09	2.39E-12
Benomyl	Soil	4.98E-08	2.64E-11	0.193	9.61E-09	5.10E-12
Bentazone	Air	2.47E-10	1.37E-11	0.117	2.88E-11	1.59E-12
Bentazone	Soil	1.61E-10	8.53E-12	0.117	1.87E-11	9.94E-13
Benzene. 1-methyl-2-nitro-	Air	4.37E-10	5.88E-12	0.102	4.46E-11	6.01E-13
Bifenox	Soil	1.30E-08	1.98E-16	0.041	5.32E-10	8.10E-18
Bitertanol	Soil	5.48E-09	3.59E-17	0.125	6.82E-10	4.47E-18
Bromoxynil	Soil	3.27E-08	9.00E-14	0.051	1.65E-09	4.55E-15
Bromuconazole	Soil	1.48E-16	8.04E-18	0.111	1.65E-17	8.96E-19
Carbaryl	Air	6.75E-11	3.73E-12	0.070	4.70E-12	2.60E-13
Carbaryl	Soil	5.39E-11	9.07E-13	0.070	3.75E-12	6.32E-14
Carbendazim	Soil	1.76E-07	2.08E-10	0.220	3.87E-08	4.56E-11
Carbetamide	Soil	1.80E-07	2.50E-09	0.119	2.13E-08	2.96E-10
Carbofuran	Soil	2.73E-05	1.45E-08	0.063	1.73E-06	9.17E-10
Carfentrazone-ethyl	Air	7.41E-12	4.10E-13	0.102	7.56E-13	4.18E-14
Carfentrazone-ethyl	Soil	5.08E-10	1.76E-14	0.102	5.17E-11	1.79E-15
Chloramine	Air	4.64E-08	2.99E-11	0.272	1.26E-08	8.15E-12
Chloramine	Water	4.14E-07	2.67E-10	0.272	1.13E-07	7.28E-11
Chloridazon	Soil	1.32E-14	7.17E-16	0.190	2.51E-15	1.36E-16
Chlorimuron-ethyl	Air	1.35E-10	7.46E-12	0.135	1.82E-11	1.01E-12
Chlorimuron-ethyl	Soil	2.51E-09	1.88E-10	0.135	3.39E-10	2.53E-11
Chlormequat	Soil	8.28E-09	2.18E-10	0.114	9.46E-10	2.49E-11
Chlorothalonil	Soil	1.29E-04	8.84E-09	0.105	1.36E-05	9.32E-10
Chlorpyrifos	Air	2.69E-09	1.49E-10	0.040	1.08E-10	5.95E-12
Chlorpyrifos	Soil	1.90E-08	1.41E-09	0.040	7.59E-10	5.62E-11
Chlorsulfuron	Soil	2.05E-16	1.11E-17	0.196	4.00E-17	2.17E-18
Chlortoluron	Soil	1.45E-04	8.97E-12	0.132	1.92E-05	1.18E-12
Choline chloride	Soil	2.82E-14	1.53E-15	0.100	2.83E-15	1.53E-16
Cinidon-ethyl	Soil	6.39E-12	3.38E-13	0.036	2.27E-13	1.20E-14
Clethodim	Air	3.99E-10	2.21E-11	0.039	1.55E-11	8.59E-13
Clethodim	Soil	3.59E-09	2.68E-10	0.039	1.40E-10	1.04E-11
Clodinafop-propargyl	Soil	3.03E-15	1.64E-16	0.040	1.21E-16	6.57E-18
Clomazone	Soil	4.74E-09	6.94E-11	0.058	2.77E-10	4.06E-12
Clopyralid	Soil	1.27E-09	1.62E-12	0.073	9.26E-11	1.18E-13
Cloquintocet-mexyl	Soil	7.31E-16	3.96E-17	0.042	3.05E-17	1.65E-18
Cloransulam-methyl	Air	7.03E-11	3.89E-12	0.163	1.14E-11	6.33E-13
Cloransulam-methyl	Soil	1.08E-09	8.05E-11	0.163	1.76E-10	1.31E-11
Cyanide	Air	2.00E-04	6.03E-07	0.538	1.08E-04	3.25E-07
Cyanide	Water	1.02E-04	2.67E-06	0.538	5.47E-05	1.44E-06
Cyanoacetic acid	Air	3.96E-08	9.86E-12	0.165	6.53E-09	1.62E-12
Cyfluthrin	Air	1.41E-11	7.79E-13	0.032	4.54E-13	2.51E-14
Cyfluthrin	Soil	4.04E-11	2.62E-12	0.032	1.30E-12	8.44E-14
Cyhalothrin. gamma-	Air	1.62E-10	8.94E-12	0.031	5.03E-12	2.78E-13
Cyhalothrin. gamma-	Soil	6.93E-12	3.83E-13	0.031	2.16E-13	1.19E-14
Cypermethrin	Air	3.42E-11	1.89E-12	0.034	1.15E-12	6.36E-14
Cypermethrin	Soil	3.87E-06	2.23E-09	0.034	1.30E-07	7.50E-11

Substance	Comp.	Inventory results [g/kg]		Reactive nitrogen results [g/kg]		
		Barley conventional	Barley organic	N. coeff.	Barley conventional	Barley organic
Cyproconazole	Soil	7.22E-07	4.09E-12	0.144	1.04E-07	5.89E-13
Cyprodinil	Soil	3.01E-06	4.83E-12	0.187	5.62E-07	9.02E-13
Deltamethrin	Soil	1.02E-09	3.02E-12	0.028	2.83E-11	8.37E-14
Dicrotophos	Soil	7.24E-10	5.70E-11	0.059	4.27E-11	3.37E-12
Diethylamine	Air	7.12E-09	1.53E-11	0.192	1.36E-09	2.92E-12
Diethylamine	Water	1.71E-08	3.66E-11	0.192	3.27E-09	7.02E-12
Difenoconazole	Soil	4.12E-10	6.11E-12	0.103	4.27E-11	6.32E-13
Diflubenzuron	Air	7.41E-12	4.10E-13	0.090	6.69E-13	3.70E-14
Diflubenzuron	Soil	7.16E-07	5.34E-08	0.090	6.46E-08	4.82E-09
Diflufenican	Soil	6.30E-08	1.23E-11	0.071	4.47E-09	8.73E-13
Diflufenzopyr-sodium	Soil	2.69E-11	2.65E-14	0.157	4.24E-12	4.16E-15
Dimethachlor	Soil	1.16E-08	1.69E-10	0.055	6.33E-10	9.28E-12
Dimethenamid	Soil	9.53E-10	8.11E-12	0.051	4.84E-11	4.12E-13
Dimethoate	Soil	5.48E-10	2.90E-11	0.061	3.35E-11	1.77E-12
Dimethylamine	Air	1.22E-11	2.89E-13	0.311	3.80E-12	8.99E-14
Dimethylamine	Water	2.53E-07	1.44E-10	0.311	7.86E-08	4.48E-11
Dinitrogen monoxide	Air	2.44E+00	2.78E+00	0.636	1.55E+00	1.77E+00
Dipropylamine	Air	4.39E-09	7.53E-12	0.138	6.07E-10	1.04E-12
Dipropylamine	Water	1.05E-08	1.81E-11	0.138	1.46E-09	2.50E-12
Diquat	Soil	7.68E-09	4.07E-12	0.152	1.17E-09	6.19E-13
Diquat dibromide	Soil	5.27E-16	4.45E-19	0.081	4.29E-17	3.62E-20
Dithianone	Soil	5.27E-11	2.79E-12	0.095	4.98E-12	2.64E-13
Diuron	Soil	1.11E-09	8.77E-11	0.120	1.34E-10	1.05E-11
Epoxiconazole	Soil	1.13E-08	3.64E-12	0.127	1.44E-09	4.64E-13
Esfenvalerate	Air	8.42E-11	4.66E-12	0.033	2.81E-12	1.55E-13
Esfenvalerate	Soil	4.61E-12	2.52E-13	0.033	1.54E-13	8.42E-15
Ethalfluralin	Soil	3.86E-09	5.65E-11	0.126	4.86E-10	7.12E-12
Ethylamine	Air	1.96E-09	5.04E-11	0.311	6.10E-10	1.57E-11
Ethylamine	Water	4.71E-09	1.21E-10	0.311	1.46E-09	3.76E-11
Ethylene diamine	Air	1.49E-08	5.14E-11	0.466	6.94E-09	2.40E-11
Ethylene diamine	Water	3.61E-08	1.24E-10	0.466	1.68E-08	5.78E-11
Fenbuconazole	Soil	1.38E-11	7.29E-13	0.166	2.29E-12	1.21E-13
Fenoxaprop	Air	1.10E-10	6.10E-12	0.042	4.63E-12	2.56E-13
Fenoxaprop	Soil	2.15E-09	1.61E-10	0.042	9.03E-11	6.75E-12
Fenoxaprop-P ethyl ester	Soil	3.77E-09	2.29E-17	0.039	1.46E-10	8.86E-19
Fenpiclonil	Soil	1.25E-08	3.48E-10	0.118	1.48E-09	4.11E-11
Fenpropidin	Soil	1.66E-07	1.16E-11	0.051	8.49E-09	5.94E-13
Fenpropimorph	Soil	1.36E-04	2.49E-11	0.046	6.29E-06	1.15E-12
Fipronil	Soil	4.37E-09	3.41E-10	0.128	5.60E-10	4.37E-11
Florasulam	Soil	1.38E-09	9.13E-18	0.195	2.69E-10	1.78E-18
Fluazifop-p-butyl	Air	1.58E-10	8.75E-12	0.037	5.78E-12	3.20E-13
Fluazifop-P-butyl	Soil	3.57E-09	9.52E-11	0.037	1.30E-10	3.48E-12
Flucarbazone sodium salt	Soil	1.28E-17	6.93E-19	0.134	1.71E-18	9.28E-20
Fludioxonil	Soil	3.25E-09	3.70E-17	0.113	3.66E-10	4.18E-18
Flufenacet	Air	5.93E-11	3.28E-12	0.116	6.86E-12	3.79E-13
Flufenacet	Soil	5.52E-08	1.41E-13	0.116	6.38E-09	1.63E-14
Flumetsulam	Air	1.39E-11	7.67E-13	0.215	2.99E-12	1.65E-13
Flumetsulam	Soil	4.78E-11	7.92E-14	0.215	1.03E-11	1.71E-14

Substance	Comp.	Inventory results [g/kg]		Reactive nitrogen results [g/kg]		
		Barley conventional	Barley organic	N. coeff.	Barley conventional	Barley organic
Flumiclorac-pentyl	Air	2.37E-11	1.31E-12	0.033	7.85E-13	4.34E-14
Flumiclorac-pentyl	Soil	1.02E-12	5.63E-14	0.033	3.36E-14	1.86E-15
Flumioxazin	Air	2.40E-10	1.33E-11	0.079	1.90E-11	1.05E-12
Flumioxazin	Soil	1.25E-09	9.35E-11	0.079	9.91E-11	7.39E-12
Fluroxypyr	Soil	2.33E-09	8.37E-13	0.110	2.56E-10	9.19E-14
Flurtamone	Soil	5.76E-08	7.39E-12	0.042	2.42E-09	3.11E-13
Flusilazole	Soil	6.32E-09	2.54E-12	0.133	8.43E-10	3.39E-13
Fomesafen	Air	8.93E-10	4.94E-11	0.064	5.70E-11	3.15E-12
Fomesafen	Soil	8.24E-09	6.15E-10	0.064	5.26E-10	3.93E-11
Foramsulfuron	Soil	5.05E-12	4.96E-15	0.186	9.39E-13	9.22E-16
Formamide	Air	2.37E-08	5.71E-12	0.311	7.37E-09	1.78E-12
Formamide	Water	5.69E-08	1.37E-11	0.311	1.77E-08	4.26E-12
Glyphosate	Air	1.79E-07	9.87E-09	0.083	1.48E-08	8.18E-10
Glyphosate	Soil	6.46E-05	2.47E-07	0.083	5.35E-06	2.04E-08
Imazamox	Air	3.55E-11	1.96E-12	0.138	4.89E-12	2.70E-13
Imazamox	Soil	1.08E-09	8.06E-11	0.138	1.48E-10	1.11E-11
Imazapyr	Soil	6.74E-13	6.62E-16	0.161	1.08E-13	1.06E-16
Imazaquin	Air	1.13E-10	6.26E-12	0.135	1.53E-11	8.45E-13
Imazaquin	Soil	4.85E-12	2.68E-13	0.135	6.55E-13	3.62E-14
Imazethapyr	Air	2.34E-10	1.30E-11	0.145	3.40E-11	1.88E-12
Imazethapyr	Soil	2.69E-09	2.01E-10	0.145	3.91E-10	2.92E-11
Imidacloprid	Soil	2.98E-08	3.34E-10	0.274	8.16E-09	9.14E-11
Ioxynil	Soil	1.99E-08	1.61E-11	0.038	7.50E-10	6.08E-13
Iprodione	Soil	5.17E-09	7.58E-11	0.127	6.58E-10	9.65E-12
Isocyanic acid	Air	5.57E-06	2.33E-07	0.326	1.81E-06	7.60E-08
Isopropylamine	Air	7.56E-10	1.82E-11	0.237	1.79E-10	4.31E-12
Isopropylamine	Water	1.82E-09	4.37E-11	0.237	4.30E-10	1.03E-11
Isoproturon	Soil	3.52E-04	1.48E-10	0.136	4.77E-05	2.01E-11
Isoxaflutole	Soil	8.08E-11	7.94E-14	0.039	3.15E-12	3.10E-15
Kresoxim-methyl	Soil	5.79E-10	4.33E-12	0.045	2.59E-11	1.94E-13
Lactofen	Air	1.14E-10	6.31E-12	0.030	3.46E-12	1.91E-13
Lactofen	Soil	4.89E-12	2.70E-13	0.030	1.48E-13	8.20E-15
Lambda-cyhalothrin	Soil	7.21E-09	3.63E-11	0.031	2.24E-10	1.13E-12
Linuron	Soil	8.65E-07	2.61E-08	0.112	9.72E-08	2.93E-09
Mancozeb	Soil	4.13E-07	1.15E-08	0.104	4.27E-08	1.19E-09
Mefenpyr	Soil	1.35E-08	1.27E-13	0.088	1.19E-09	1.12E-14
Mefenpyr-diethyl	Soil	7.54E-09	4.58E-17	0.075	5.66E-10	3.44E-18
Mepiquat chloride	Soil	5.32E-08	7.69E-12	0.094	4.98E-09	7.20E-13
Mesotrione	Soil	2.19E-10	2.15E-13	0.041	9.04E-12	8.88E-15
Metamitron	Soil	1.01E-09	8.95E-13	0.277	2.79E-10	2.48E-13
Metazachlor	Soil	2.73E-08	4.00E-10	0.151	4.13E-09	6.05E-11
Methylamine	Air	2.03E-08	1.22E-11	0.451	9.17E-09	5.50E-12
Methylamine	Water	4.88E-08	2.93E-11	0.451	2.20E-08	1.32E-11
Metolachlor	Air	1.86E-09	1.03E-10	0.049	9.20E-11	5.09E-12
Metolachlor	Soil	3.58E-07	2.59E-08	0.049	1.77E-08	1.28E-09
Metribuzin	Air	7.40E-10	4.09E-11	0.261	1.93E-10	1.07E-11
Metribuzin	Soil	2.32E-08	1.05E-09	0.261	6.05E-09	2.74E-10
Monocrotophos	Soil	8.75E-08	6.52E-09	0.063	5.49E-09	4.10E-10

Substance	**Comp.**	**Inventory results [g/kg]** **Barley conventional**	**Barley organic**	**Reactive nitrogen results [g/kg]** **N. coeff.**	**Barley conventional**	**Barley organic**
Monoethanolamine	Air	1.04E-05	1.05E-07	0.229	2.38E-06	2.40E-08
Monoethanolamine	Water	4.63E-09	1.10E-10	0.229	1.06E-09	2.51E-11
Napropamide	Soil	1.32E-07	1.83E-09	0.052	6.79E-09	9.47E-11
Nitrate	Air	1.46E-05	6.85E-07	0.226	3.30E-06	1.55E-07
Nitrate	Water	1.27E+02	1.21E+02	0.226	2.88E+01	2.72E+01
Nitrate	Soil	1.62E-05	1.07E-06	0.226	3.67E-06	2.43E-07
Nitrite	Water	1.76E-05	5.11E-07	0.304	5.35E-06	1.56E-07
Nitrobenzene	Air	4.38E-05	4.59E-11	0.114	4.99E-06	5.22E-12
Nitrobenzene	Water	1.76E-04	1.84E-10	0.114	2.00E-05	2.09E-11
Nitrogen	Air	9.49E-04	3.28E-06	0.000	0.00E+00	0.00E+00
Nitrogen	Water	5.92E-03	4.48E-05	1.000	5.92E-03	4.48E-05
Nitrogen	Soil	2.24E-06	5.73E-07	1.000	2.24E-06	5.73E-07
Nitrogen fluoride	Air	3.65E-15	1.12E-15	0.197	7.21E-16	2.21E-16
Nitrogen oxides	Air	1.85E+00	1.54E+00	0.304	5.65E-01	4.69E-01
Nitrogen. organic bound	Water	1.22E-03	1.99E-04	0.160	1.95E-04	3.19E-05
Orbencarb	Soil	7.85E-08	2.18E-09	0.054	4.26E-09	1.19E-10
Parathion	Soil	3.46E-10	8.31E-11	0.048	1.66E-11	3.99E-12
Particulates. < 10 µm	Air	5.52E-02	6.27E-02	0.054	2.99E-03	3.40E-03
Particulates. < 2.5µm	Air	2.37E-01	6.28E-02	0.081	1.91E-02	5.06E-03
Particulates. > 2.5µm. < 10µm	Air	1.55E-01	1.15E-03	0.028	4.32E-03	3.22E-05
Pendimethalin	Air	5.01E-09	2.77E-10	0.149	7.49E-10	4.14E-11
Pendimethalin	Soil	1.56E-04	4.77E-09	0.149	2.33E-05	7.12E-10
Phenmedipham	Soil	1.85E-10	1.64E-13	0.093	1.72E-11	1.53E-14
Propiconazole	Air	8.75E-11	4.84E-12	0.123	1.07E-11	5.94E-13
Propiconazole	Soil	6.22E-08	3.27E-12	0.123	7.64E-09	4.02E-13
Propylamine	Air	1.24E-10	1.96E-12	0.237	2.93E-11	4.65E-13
Propylamine	Water	2.97E-10	4.71E-12	0.237	7.03E-11	1.12E-12
Simazine	Soil	3.40E-10	3.34E-13	0.347	1.18E-10	1.16E-13
Sulfentrazone	Air	5.69E-10	3.15E-11	0.145	8.24E-11	4.55E-12
Sulfentrazone	Soil	1.29E-08	9.67E-10	0.145	1.87E-09	1.40E-10
t-Butylamine	Air	2.80E-08	2.39E-11	0.192	5.37E-09	4.58E-12
t-Butylamine	Water	6.73E-08	5.74E-11	0.192	1.29E-08	1.10E-11
Tebupirimphos	Soil	1.41E-10	1.39E-13	0.088	1.24E-11	1.22E-14
Tebutam	Soil	5.02E-07	6.95E-09	0.060	3.01E-08	4.17E-10
Tralkoxydim	Soil	1.29E-07	7.86E-16	0.043	5.47E-09	3.34E-17
Trifloxystrobin	Air	5.19E-12	2.87E-13	0.069	3.56E-13	1.97E-14
Trifloxystrobin	Soil	7.45E-09	1.24E-14	0.069	5.11E-10	8.50E-16
Trifluralin	Air	8.20E-09	4.53E-10	0.125	1.03E-09	5.68E-11
Trifluralin	Soil	1.64E-07	6.99E-09	0.125	2.06E-08	8.76E-10
Trimethylamine	Air	2.45E-10	3.30E-12	0.237	5.79E-11	7.82E-13
Trimethylamine	Water	5.87E-10	7.92E-12	0.237	1.39E-10	1.88E-12
Urea	Water	1.14E-09	1.61E-11	0.466	5.33E-10	7.50E-12
Total	**-**	-	-	-	**3.30E+01**	**2.98E+01**

Results show a greater impact, calculated as reactive nitrogen, for the conventional barley cultivation alternative (32.998 g/kg compared to 29.785 g/kg of the organic cultivation). Again, the considerations made in the previous paragraph, concerning dinitrogen monoxide and particulates emissions, apply.

As in previous applications, the contribution of the main substances to the reactive nitrogen indicator was also calculated, obtaining the results shown in the Figure 4.4.

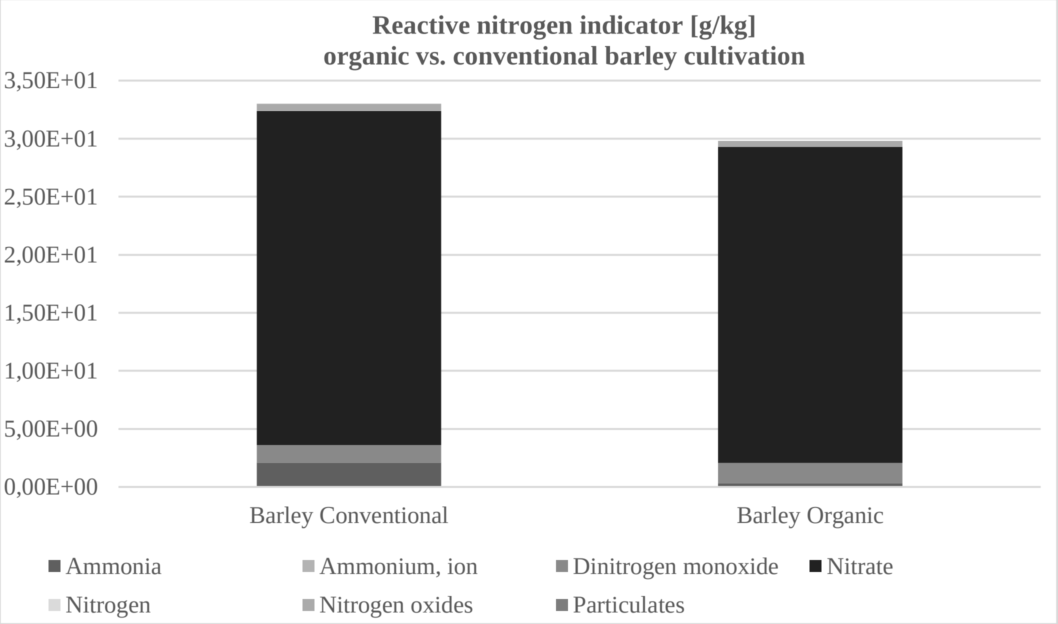


Figure 4.4. *Reactive nitrogen indicator results showing output substances contribution (percentage > 0.02% referred to conventional system) with reference to the conventional and organic barley cultivation.*

Once again, the results showed a high contribution for the same substances found in the previous applications, with particular reference to nitrate emissions to water, making a contribution of about 90% for both cultivation alternatives.

4.3.4 Agricultural processes: characterization

Starting from the nitrogen inventory results, the nitrogen impact assessment profile was calculated, by applying the characterization factors to the nitrogen-containing substances. The results obtained for conventional and organic barley product systems are reported in the Table 4.19 where the nitrogen-containing substance for which characterization factors are defined by the models used are listed for each impact category. For simplicity of calculation a cut-off criterion was applied, limited to the impact categories freshwater ecotoxicity, human toxicity cancer effect and human toxicity non-cancer effect, excluding the substances which made a contribution of less than 0.01% to the total impact of each category.

Table 4.19. *Nitrogen impact assessment profile calculated for conventional and organic barley product systems. Cut-off criterion of 0.01% applied for the categories Freshwater ecotoxicity, Human toxicity cancer effect and Human toxicity non-cancer effect.*

Impact category	Substance	Comp.	Unit	Barley Conv.	Barley Org.
Climate change	Dinitrogen monoxide	Air	kg CO2 eq	6.47E-01	7.38E-01
Climate change	Nitrogen fluoride	Air	kg CO2 eq	5.87E-14	1.80E-14
Climate change		**Total**	**kg CO2 eq**	**6.47E-01**	**7.38E-01**
Human toxicity, cancer eff.		**Total**	**CTUh**	**0.00E+00**	**0.00E+00**
Human toxicity, non-canc. eff.		**Total**	**CTUh**	**0.00E+00**	**0.00E+00**
Particulate matter	Ammonia	Air	kg PM2.5 eq	1.67E-04	2.39E-05
Particulate matter	Nitrogen oxides	Air	kg PM2.5 eq	1.35E-05	1.11E-05
Particulate matter	Particulates. < 10μm	Air	kg PM2.5 eq	1.26E-05	1.43E-05
Particulate matter	Particulates. < 2.5μm	Air	kg PM2.5 eq	4.03E-04	6.35E-05
Particulate matter		**Total**	**kg PM2.5 eq**	**5.96E-04**	**1.13E-04**
Photochemical ozone formation	Nitrogen oxides	Air	kg NMVOC eq	1.85E-03	1.54E-03
Photochemical ozone formation		**Total**	**kg NMVOC eq**	**1.85E-03**	**1.54E-03**
Acidification	Ammonia	Air	molc H+ eq	7.57E-03	1.08E-03
Acidification	Nitrogen oxides	Air	molc H+ eq	1.37E-03	1.14E-03
Acidification		**Total**	**molc H+ eq**	**8.94E-03**	**2.22E-03**
Terrestrial eutrophication	Ammonia	Air	molc N eq	3.38E-02	4.84E-03
Terrestrial eutrophication	Nitrate	Air	molc N eq	4.61E-08	2.17E-09
Terrestrial eutrophication	Nitrogen oxides	Air	molc N eq	7.90E-03	6.57E-03
Terrestrial eutrophication		**Total**	**molc N eq**	**4.17E-02**	**1.14E-02**
Marine eutrophication	Ammonia	Air	kg N eq	2.30E-04	3.30E-05
Marine eutrophication	Ammonium. ion	Water	kg N eq	1.11E-05	7.56E-08
Marine eutrophication	Nitrate	Air	kg N eq	4.09E-10	1.92E-11
Marine eutrophication	Nitrate	Water	kg N eq	2.88E-02	2.73E-02
Marine eutrophication	Nitrite	Water	kg N eq	5.35E-09	1.55E-10
Marine eutrophication	Nitrogen oxides	Air	kg N eq	7.22E-04	6.00E-04
Marine eutrophication		**Total**	**kg N eq**	**2.98E-02**	**2.79E-02**
Freshwater ecotoxicity	Carbofuran	Soil	CTUe	5.90E-04	3.13E-07
Freshwater ecotoxicity	Chlorothalonil	Soil	CTUe	7.46E-03	5.11E-07
Freshwater ecotoxicity	Isoproturon	Soil	CTUe	3.33E-03	1.40E-09
Freshwater ecotoxicity	Pendimethalin	Soil	CTUe	4.57E-04	1.40E-08
Freshwater ecotoxicity		**Total**	**CTUe**	**1.18E-02**	**8.39E-07**

In this case, as best highlighted in the following graphs reporting normalization and weighting results, the organic cultivation alternative showed less environmental impacts for all the considered categories except for the impact category climate change. The result is also in this case due to the emissions of dinitrogen monoxide, which is the nitrogen-containing substance that gives the greatest contribution to the impact category climate change. By making a comprehensive impact assessment, in relation to the climate change category, it is noted that the contribution of the dinitrogen emissions is balanced by the contribution of carbon dioxide emissions largely arising from the post-seeding fertilization process by urea, only carried out for the conventional barley cultivation. In fact, applying the IPCC 2013 GWP 100a (Stocker *et al.,* 2013), the results indicate a total impact equal to 0.931 kg CO_2 equiv. for conventional cultivation compared to 0.794 kg CO_2 equiv. for organic cultivation.

It is also noted that, by applying the cut-off criterion described above, no nitrogen-containing substances were attributed to the impact categories human toxicity cancer effect and human toxicity non-cancer effect for both the analyzed product systems, thus resulting an impact equal to 0 for these categories.

4.3.5 Agricultural processes: normalization and weighting

The last step of the methodology provides for the final calculation of the single score nitrogen impact indicator, after execution of normalization and calculation and application of the weighting factors. The nitrogen impact assessment profile results after normalization are shown, for both the cultivation alternative, in the Table 4.20.

Table 4.20. *Results of normalized impact assessment profile calculated for conventional and organic barley product systems. Normalization factors extracted from Benini et al. (2014).*

Category	**Conventional barley category results**	**Organic barley category results**	**Normalization factors**	**Conv. barley normal.**	**Org. barley normal.**
Climate change	6.47E-01 kg CO_2 eq	7.38E-01 kg CO_2 eq	9.22E+03	7.01E-05	8.00E-05
Particulate matter	5.96E-04 kg $PM_{2.5}$ eq	1.13E-04 kg $PM_{2.5}$ eq	3.80E+00	1.57E-04	2.97E-05
Photochemical ozone form.	1.85E-03 kg NMVOC eq	1.54-03 kg NMVOC eq	3.17E+01	5.85E-05	4.86E-05
Acidification	8.94E-03 molc H^+ eq	2.22E-03 molc H^+ eq	4.73E+01	1.89E-04	4.70E-05
Terrestrial eutrophication	4.17E-02 molc N eq	1.14E-02 molc N eq	1.76E+02	2.37E-04	6.48E-05
Marine eutrophication	2.98E-02 kg N eq	2.79E-02 kg N eq	1.69E+01	1.76E-03	1.65E-03
Freshwater ecotoxicity	1.18E-02 CTUe	8.39E-07 CTUe	8.74E+03	1.35E-06	9.60E-11
Human tox., canc. eff-	0.00E+00 CTUh	0.00E+00 CTUh	3.69E-05	0.00E+00	0.00E+00

Category	Conventional barley category results	Organic barley category results	Normalization factors	Conv. barley normal.	Org. barley normal.
Human tox., non-canc. eff.	0.00E+00 CTUh	0.00E+00 CTUh	5.33E-04	0.00E+00	0.00E+00

In terms of comparison, the same considerations made with regard to the results of the characterization can be applied, the organic barley presenting less environmental impact for all considered categories, except for climate change.

As already stated, normalized results can also be represented in a single graphic form, as shown in the Figure 4.5.

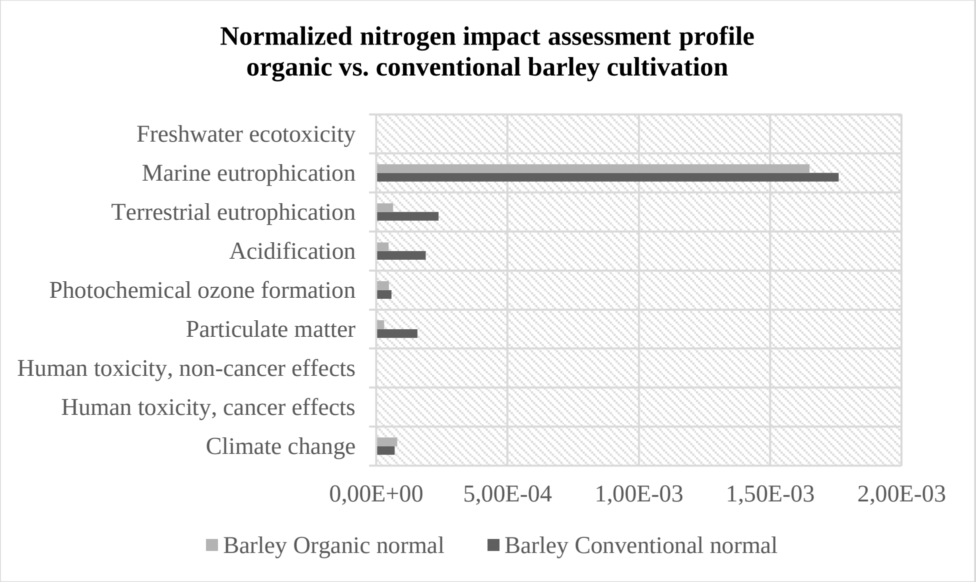


Figure 4.5. *Normalized impact assessment profile results: comparison between organic and conventional barley product systems.*

After the normalization operation, a first comparison can be made between the results of the different impact categories: also in this case, as already proved in the previous applications, it is evident the greater impact of the category marine eutrophication, compared to results of the other selected impact categories.

To reach the final result, the weighting factors were then calculated, applying the internal method provided by the proposed methodology. Unlike what was seen for the reference product system application, in this case was necessary to calculate the reactive nitrogen for each impact category referred to both the product systems as the sum of the category reactive nitrogen of each product system, the analysis being extended to more than one entity. The results of the calculation of the weighting factors are presented in the Table 4.21.

Table 4.21. *Results of weighting factors calculation obtained applying the method of calculation provided by the proposed methodology in the case of different product systems.*

Impact category	Substance	Reactive N barley conv. [kg/kg]	Reactive N barley org. [kg/kg]	Reactive N product systems	Weighting factors
Climate change	Dinitrogen monoxide	1.55E-03	1.77E-03		
Climate change	Nitrogen fluoride	7.21E-19	2.21E-19		
Climate change	**Total**	**1.55E-03**	**1.77E-03**	**3.33E-03**	**4.4951%**
Human tox. canc. eff.	**Total**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.0000%**
Human tox. non-canc. eff.	**Total**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.0000%**
Particulate matter	Ammonia	2.06E-03	2.95E-04		
Particulate matter	Nitrogen oxides	5.65E-04	4.69E-04		
Particulate matter	Particulates, < 10 mm	2.99E-06	3.40E-06		
Particulate matter	Particulates, < 2.5 mm	1.91E-05	5.06E-06		
Particulate matter	**Total**	**2.65E-03**	**7.73E-04**	**3.42E-03**	**4.6228%**
Photochemical ozone form.	Nitrogen oxides	5.65E-04	4.69E-04		
Photochemical ozone form.	**Total**	**5.65E-04**	**4.69E-04**	**1.03E-03**	**1.3979%**
Acidification	Ammonia	2.06E-03	2.95E-04		
Acidification	Nitrogen oxides	5.65E-04	4.69E-04		
Acidification	**Total**	**2.62E-03**	**7.64E-04**	**3.39E-03**	**4.5815%**
Terrestrial eutrophication	Ammonia	2.06E-03	2.95E-04		
Terrestrial eutrophication	Nitrate	3.30E-09	1.55E-10		
Terrestrial eutrophication	Nitrogen oxides	5.65E-04	4.69E-04		
Terrestrial eutrophication	**Total**	**2.62E-03**	**7.64E-04**	**3.39E-03**	**4.5815%**
Marine eutrophication	Ammonia	2.06E-03	2.95E-04		
Marine eutrophication	Ammonium, ion	1.11E-05	7.55E-08		
Marine eutrophication	Nitrate	3.30E-09	1.55E-10		
Marine eutrophication	Nitrate	2.88E-02	2.72E-02		
Marine eutrophication	Nitrite	5.35E-09	1.56E-10		
Marine eutrophication	Nitrogen oxides	5.65E-04	4.69E-04		
Marine eutrophication	**Total**	**3.14E-02**	**2.80E-02**	**5.94E-02**	**80.3210%**
Freshwater ecotoxicity	Carbofuran	1.73E-09	9.17E-13		
Freshwater ecotoxicity	Chlorothalonil	1.36E-08	9.32E-13		
Freshwater ecotoxicity	Isoproturon	4.77E-08	2.01E-14		
Freshwater ecotoxicity	Pendimethalin	2.33E-08	7.12E-13		
Freshwater ecotoxicity	**Total**	**8.64E-08**	**2.58E-12**	**8.64E-08**	**0.0001%**
Product systems total				**7.40E-02**	**100%**

From the weighting factors calculation, was obtained as a result, also in this case, an high value for the weighting factor of the category marine eutrophication compared to the values obtained for the other categories and a very low value for the category freshwater ecotoxicity. No value was calculated for the categories human toxicity cancer effect and human toxicity non-cancer effect to which no nitrogen-containing substances were attributed.

Calculated weighting factors application to the normalized results produced the weighted nitrogen impact assessment profile, whose results are reported in the Table 4.22 also showing the results obtained for the single score nitrogen impact indicator as the summation of categories weighted results. After weighting, is even more evident the difference between the results for the category marine eutrophication and the results of other impact categories.

Table 4.22. *Weighted nitrogen assessment profile (last two columns) and single score nitrogen impact indicator (last row) results calculated for conventional and organic barley product systems.*

Category	**Barley conv. normal.**	**Barley org. normal.**	**Weighting factors**	**Barley conv. weight.**	**Barley org. weight.**
Climate change	7.01E-05	8.00E-05	4.50%	3.15E-06	3.60E-06
Human toxicity, cancer effects	0.00E+00	0.00E+00	0.00%	0.00E+00	0.00E+00
Human toxicity, non-cancer effects	0.00E+00	0.00E+00	0.00%	0.00E+00	0.00E+00
Particulate matter	1.57E-04	2.97E-05	4.62%	7.25E-06	1.37E-06
Photochemical ozone formation	5.85E-05	4.86E-05	1.40%	8.18E-07	6.80E-07
Acidification	1.89E-04	4.70E-05	4.58%	8.66E-06	2.15E-06
Terrestrial eutrophication	2.37E-04	6.48E-05	4.58%	1.09E-05	2.97E-06
Marine eutrophication	1.76E-03	1.65E-03	80.32%	1.41E-03	1.33E-03
Freshwater ecotoxicity	1.35E-06	9.60E-11	0.0001%	1.58E-12	1.12E-16
Total (single score nitrogen impact indicator)				**1.44E-03**	**1.34E-03**

The results of the single score nitrogen impact indicator is also shown in graphical form in Figure 4.6.

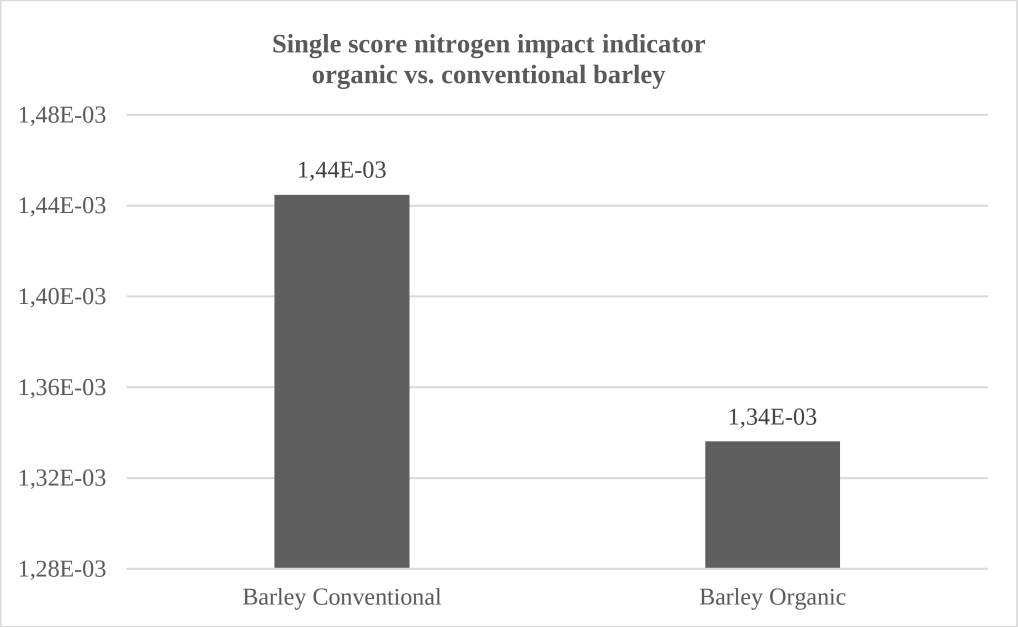


Figure 4.6. *Single score nitrogen impact indicator results calculated for conventional and organic barley product systems.*

The final result indicates a greater overall impact, related to the nitrogen cycle, for the conventional barley cultivation alternative (+8.1% compared to organic cultivation alternative).

4.3.6 Agricultural processes: interpretation of the results

In addition to what has been highlighted in the preceding paragraphs within the presentation of the results obtained, the following is to be noted in relation to the objectives set for the application:

- All the operative steps of the proposed methodology were applied for the comparison between two cultivation alternatives (conventional and organic) for the production of 1 kg of barley, allowing the calculation of nitrogen inventory results, reactive nitrogen indicator, nitrogen impact assessment profile (subsequently normalized and weighted) and single score nitrogen impact indicator, after determining the internal weighting factors. The methodology was therefore successfully tested in an application case based on real data, providing useful results for the comparison.
- The application allowed in particular comparing the cultivation alternatives with reference to all the outputs provided by the proposed methodology, by highlighting the differences and allowing to determine the preferred environmental alternative with reference to the impacts associated with

the nitrogen cycle. The application also allowed testing the weighting factor calculation by the internal weighting method proposed in the case of two different product systems.

As for the results obtained, the conventional system cultivation showed greater environmental impacts than the organic one considering the aggregate indicators (reactive nitrogen and single score impact). The methodology also allowed to highlight that these results were mainly attributable to the emissions derived from the use of chemical fertilizers and pesticides, not used in the organic cultivation system. Other important impact sources were due to the fertilizer production and to the production of the seeds used in the sowing phase. As far as the emissions of the product systems are concerned, only with regard to emissions to air of dinitrogen monoxide and particulates < 10 μm, the organic alternative was less preferable due to the lower yield per hectare. This result is also reflected, with regard to the impact profile, in the climate change impact category, which resulted the only one for which the organic alternative was less preferable: even considering the nitrogen impact assessment profile, the organic alternative was generally the one with lower impacts for the categories related to the nitrogen cycle.

By analyzing in detail the results obtained for the reactive nitrogen indicator and for the single score nitrogen impact indicator, an analogous result was obtained as far as comparison is concerned, as highlighted in the Table 4.23 reporting the results refereed to both the indicators.

Table 4.23. *Reactive nitrogen indicator and nitrogen impact indicator results for the cultivation alternatives of 1 kg of barley. In the Δ columns is reported the percentage difference calculated for the conventional production alternative compared to the organic production alternative.*

Production alternative	**Reactive nitrogen indicator results [g/kg]**	**Δ (conventional vs organic) [%]**	**Nitrogen impact indicator results**	**Δ (conventional vs organic) [%]**
Barley conventional	3.30E+01	+ 10.8	1.44E-03	+ 8.1
Barley organic	2.98E+01	-	1.34E-03	-

In this case, besides resulting the same ranking for both indicators, the difference between the two alternatives resulted of very similar percent value, denoting a high degree of consistency between the two assessment steps of the proposed methodology. This kind of consistency of results is not always detectable, as shown in the next application results.

As a final consideration of a general nature, referring to the use of the proposed methodology for the assessment of agricultural processes, it should be noted that, unlike what was verified for nitrogen-based fertilization, the impacts associated with the use of phosphorus-based fertilizers are not adequately highlighted by the assessment. In this way, the impacts related to conventional cultivation methods, which mainly use synthetic phosphorous fertilizers, are not fully accounted, especially in comparison with organic methods. This concern leads to the need to consider a possible complementary assessment of the environmental impacts associated with nitrogen and phosphorus cycles, in particular with reference to the life-cycle analysis of agricultural and agri-food processes.

4.4 Methodology application to beverage industry products

The last application presented concerns an experimentation, based on real data collected on the field, regariding the assessment of impacts related to nitrogen cycle of four products within a beverage industry Italian company: “Birra Castello”. This specific application, described in the following paragraphs, was carried out in conjunction with a carbon footprint study commissioned by the company and recently completed.

4.4.1 Beverage industry products: goal and scope definition

The experimental application described in this section relates to four product system of the beverage industry company “Birra Castello” with the aim to assess the impacts related to the nitrogen cycle of two types of beer packaged in two different formats for a total of four product systems. Differences such as the type of beer, the size of the glass bottles, and the secondary packaging make the product systems different, although they have strong similarities.

The following objectives were identified for the application:

- provide a description of impacts related to the nitrogen cycle arising from emissions derived by all the processes involved in the life cycle of the analyzed products;
- identify the processes that make the most significant contribution to the total impact of the analyzed products;
- make a first complete application of the whole methodology in an industrial environment and deliver the results to the commissioner company.

Specifically, the analyzed ***product systems*** can be described as follows:

- “Birra Castello Premium” 33 cl packaged in single bottle produced in the Pedavena plant (BL);

- "Birra Castello Premium" 33 cl packaged in three-bottle cluster produced in the S. Giorgio di Nogaro plant (UD);
- "Birra Castello La Decisa" 33 cl packaged in single bottle produced in the S. Giorgio di Nogaro plant (UD);
- "Birra Castello La Decisa" 33 cl packaged in three-bottle cluster produced in the S. Giorgio di Nogaro plant (UD).

As for the product "La Decisa" 33 cl packaged in three-bottle cluster, the study was based on prospective data (a predefined bill of materials) as the launch on the market was scheduled after completing the study.

The Figure 4.7 shows an image of the two types of product in single bottle packaging.

Figure 4.7. *Birra Castello Premium (on the left) and Birra Castello La Decisa (on th right) single bottle packaging.*

The products perform the specific ***function*** of satisfying a human food need that can be linked to a caloric intake but more often to the need to quench.

The ***functional units*** of the analyzed systems can be described as in the Table 4.24.

Table 4.24. *Functional unit synthetic descriprion for the four products of the beverage industry.*

Beer type	**Packaging**	**Functional unit**
Birra Castello Premium 33 cl	single bottle	A Castello Premium 33cl beer, with a 4.8% alcohol content, packed in brown glass bottle, with paper labels and tin-plated crown cap, packaged in single bottle
	three-bottle cluster	A Castello Premium 33cl beer, with a 4.8% alcohol content, packed in brown glass bottle, with paper labels and tin-plated crown cap, packaged in three-bottle cardboard cluster
Birra Castello La Decisa 33cl	single bottle	A Castello La Decisa 33cl beer, with a 4.8% alcohol content, packed in brown glass bottle, with paper labels and tin-plated crown cap, packaged in single bottle
	three-bottle cluster	A Castello La Decisa 33cl beer, with a 4.8% alcohol content, packed in brown glass bottle, with paper labels and tin-plated crown cap, packaged in three-bottle cardboard cluster

System boundaries were defined including all processes attributable to products in their life cycle. All input and output streams of matter and energy were then counted for all phases of the products life cycle. Below are briefly described the main processes and related input and output considered:

- Raw materials production: barley malt, malt dye, wheat malt and hops.
- Packaging components production comprising: primary packaging such as glass bottles, labels, caps; secondary packaging, such as clusters, trays, boxes, shrink film; tertiary packaging, such as pallets, interlayers, top covers and extensible films.
- Beer productive process, comprising consumption of energy sources (eg. electricity, methane, diesel), consumption of chemical compounds used in the process and for sanitizing operations, water consumption according to different technological purposes, atmospheric emissions (eg. stack emissions, leakage of refrigerants), the production and disposal of waste from the production plant and, the wastewater treatment.
- Products distribution, considering distances and means of transport used for each of the analyzed products and materials, production and disposal of waste originating from unpacking of products (loss of tertiary and secondary packaging), energy consumption generated by points of sale.
- Phase of use, considering the transport operated by the consumer and the consumption of energy generated by the domestic product cooling.
- Products end-of-life: scenarios were used to treat the primary packaging components of the products (bottles, caps, labels).

The production and maintenance processes of capital goods related to the production were excluded from the system boundaries.

In the Figure 4.8, a simplified scheme of the processes considered throughout the entire life cycle of the products is presented using a general structure valid for the different product systems.

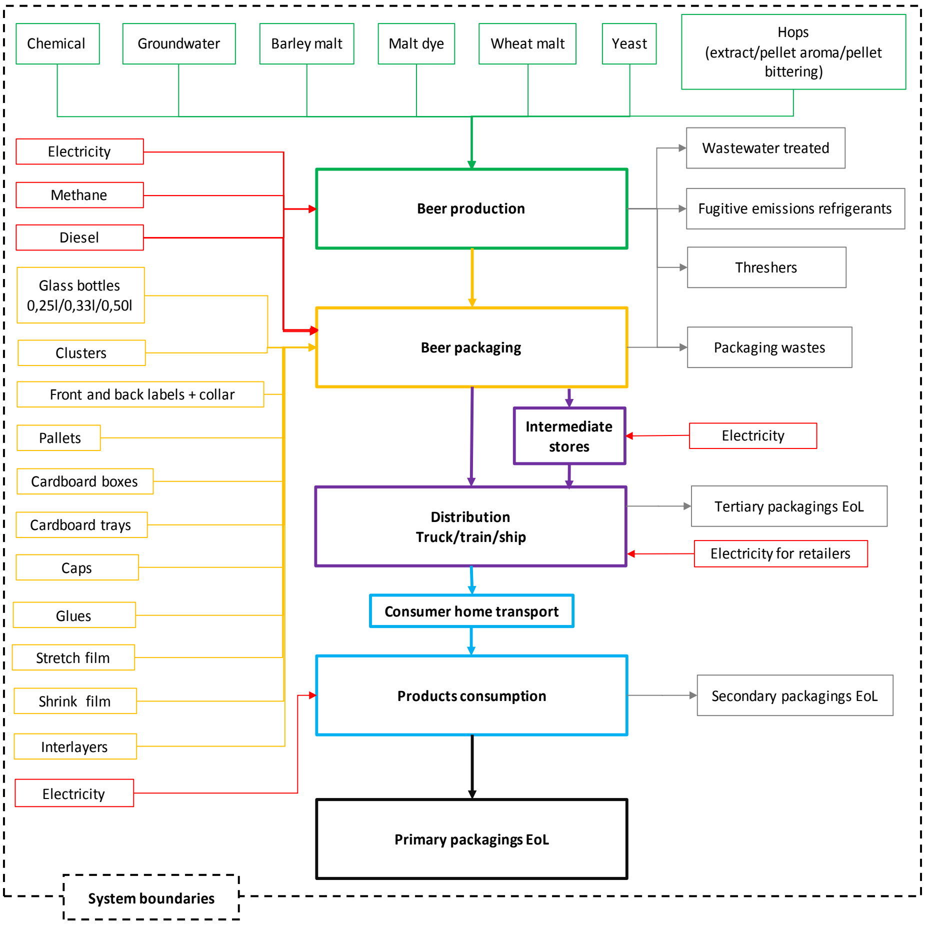


Figure 4.8. *System boundaries general scheme for the analyzed product systems of the beverage industry: different colors represent the different phases of the life cycle and the relative input and output considered. Source: Loss and Zuliani (2017).*

For the analysis, a mass-based ***cut-off criterion*** was utilized by neglecting the material flows representing less than 1% of the incoming total flow, including streams of materials for which it was impossible to collect data or with a negligible mass with respect to the process considered. However, all processes were taken into account for which data were available, although their contribution was less than 1%. This choice is confirmed by several LCA studies. Within the cut-off threshold also fall: plant construction processes, staff handling, and fewer streams of auxiliary materials. The exclusion of these flows is not such as to significantly alter the results of the study. Furthermore, the modeling of recycling operations within the product end of life was carried out using the cut-off approach that associates null impacts to these processes, as reported, among others, by Frischknecht (2010) by associating the 100% impacts of recycling operations to the next product system in which recycled material will be used.

According to LCA requirements (ISO, 2006a,b) ***allocation*** was performed on a mass basis: energy consumption (eg. electricity, methane, diesel), wastewater, consumption of chemicals, waste and atmospheric emissions (eg. stack emissions, leakage of refrigerants) were allocated to volumes produced by the two specific types of beer covered by the analysis. This choice was also supported by the fact that energy and material consumption were fairly constant and equiparable for all beer qualities. Furthermore, following a worst-case approach, as there was no information disaggregated about the initial processes involved in the production of the "couch-grass" co-product, it was decided not to allocate, imputing 100% of the impacts to the beer products.

4.4.2 Beverage industry products: inventory analysis

The approach used in collecting data was to gather the most information by privileging their representativeness and importance over the life cycle of the analyzed products. Primary data referred to the year 2016 were collected for production, packaging and distribution processes, as these aspects were directly managed by the producer Birra Castello S.p.A.

Below is a summary of the data considered for the analysis in relation to the different process units of the product systems:

- ***Production of raw materials***. The raw materials used for the production of the two types of beer are: barley malt, malt dye, wheat malt, hop (extract, pellet aroma, pellet bittering), water, yeast.
  As regards barley malt, it was accounted from the agricultural production process of barley using Ecoinvent v3.1 database that includes following processes: soil cultivation, sowing, weed control, fertilization process, pest control and pathogens, harvesting and drying of grains. Operational machines and their infrastructure are also considered. This database includes streams of fertilizers, pesticides and seeds, transportation processes at the storage center and direct field emissions. Emissions of the following processes required for the conversion of barley into barley malt were also evaluated by quantifying their energy consumption (Briggs, 1998): maceration process, germination process, roasting process and other auxiliary processes. The energy used by these processes is the result of combustion of methane gas (Briggs, 1998), whose primary flows were

modeled using the Ecoinvent v3.1 database. Finally, the emissions from the transport of barley in bulk from the supply sites to both production plants were also evaluated using database Ecoinvent. As regards malt dye, it was accounted from the agricultural production process of barley. Even in this case, the aspects of agricultural production and malting processes were included. It was considered the concentration factor for the production of malt dyes, being required about 2.66 kg of barley malt for 1 kg of malt dye (Briggs, 1998). Road transport was accounted using the Ecoinvent database considering the Italian and European actual suppliers.

As regards wheat malt, it was accounted from the corn production process. For agricultural maize production, the Agri-footprint database was used, which includes cultivation of maize, diesel consumption, use of agricultural machinery, consumption of pesticides, fertilizers and seeds and their transport to the site where the grinding process, also included, takes place. This database considers by-products, 40% of the total mass, from the grinding process of corn grains out of the mill, making a mass-based allocation. Finally, the emissions from the transport of corn flour from the sites of supply to the production plants were evaluated. Again, corn flour is transported bulk and the transport process was accounted using the previous listed database.

As regards hop, it was accounted from the agricultural production process by referring to scientific literature. Emissions from diesel fuel consumption, fuel consumption and irrigation were considered. The amount of diesel fuel used to cultivate one hectare of hop cultivation was estimated from fuel costs for the cultivation of an hectare of hop (Galinato *et al.,* 2010). Nitrogen, K_2O and P_2O_5 fertilizers were accounted using the LCA Food DK database, and finally the lime spattered on the soil was accounted using the Ecoinvent database. Quantities used were estimated using secondary data (Saleem *et al.,* 2010). Finally, the emission factor related to the irrigation process was also considered (Lal, 2004). As for the transport of hops, the different German suppliers of different types of hops were considered. The transport takes place on road and was accounted using the Ecoinvent database.

As regards water, it was accounted using database referred to artesian wells for San Giorgio di Nogaro plant and to surface water sources for Pedavena plant. The water initially undergoes a number of treatments to improve some of its chemical and physical parameters, and then undergo different treatments depending on whether it is used as dilution water, which is added to the product or as process water, used primarily as a heat carrier and for the steam production. The consumption of chemical and energy reactors for pumping in plant and production in boiler of hot water and steam was accounted.

For the yeast, the only biomass used was considered and not the industrial yeast production process, as its contribution is negligible in the production of beer (lower than 10 g for a liter of beer, see Cordella *et al.*, 2008).

Several chemical reagents with multiple functions ranging from filtering actions to cleansing and stabilizing actions are also used during the production process (detergents, hydrochloric acid, nitric acid, phosphoric acid, sodium hydroxide, calcium chloride, silica sand, fibroxcel). In this case it was assumed, according to the company's indications, that the type and use of these chemical components was influenced by production levels and not by the type of beer produced, so it was considered the consumption of chemicals in the year 2015 allocating them to the specific products analyzed on the basis of volumes produced, without distinguishing different types of beers. For each chemical, it was considered the production process and transport from the producer to the plant of San Giorgio di Nogaro and Pedavena. Primary data provided by the company were used for the quantities of chemicals used during production and database Ecoinvent for chemicals accounting.

- ***Packaging production***. The Table 4.25 lists, for each of the analyzed products, all the packaging components, subdivided in primary, secondary and tertiary and the respective considered mass.

Table 4.25. *Detailed description and mass of the packaging components for the four analyzed product systems of the beverage indsutry.*

Product	Packaging type	Packaging components	Mass [g]
Premium 33 cl single bottle	Primary packaging	33cl brown glass bottle - Fanes Model	230.00
Premium 33 cl single bottle	Primary packaging	Tinplate crown cap	2.00
Premium 33 cl single bottle	Primary packaging	Two-sided labels and paper collar	0.50
Premium 33 cl single bottle	Primary packaging	Glue for labels	2.08
Premium 33 cl single bottle	Secondary packaging	Cardboard box for 24 bottles	10.42
Premium 33 cl single bottle	Secondary packaging	Glue for boxes	0.62
Premium 33 cl single bottle	Tertiary packaging	PE top cover	0.13
Premium 33 cl single bottle	Tertiary packaging	Pallet	13.2
Premium 33 cl single bottle	Tertiary packaging	Cardboard interlayer	0.66
Premium 33 cl single bottle	Tertiary packaging	Stretch film	0.23
Premium 33 cl in cluster	Primary packaging	33cl brown glass bottle - Fanes Model	230.00
Premium 33 cl in cluster	Primary packaging	Tinplate crown cap	2.00
Premium 33 cl in cluster	Primary packaging	Two-sided labels and paper collar	0.50
Premium 33 cl in cluster	Primary packaging	Glue for labels	2.08
Premium 33 cl in cluster	Secondary packaging	Cardboard 3-bottles cluster	10.00
Premium 33 cl in cluster	Secondary packaging	Cardboard box for 24 bottles	10.42
Premium 33 cl in cluster	Secondary packaging	Glue for boxes	0.62
Premium 33 cl in cluster	Tertiary packaging	PE top cover	0.13
Premium 33 cl in cluster	Tertiary packaging	Pallet	13.2
Premium 33 cl in cluster	Tertiary packaging	Cardboard interlayer	0.66
Premium 33 cl in cluster	Tertiary packaging	Stretch film	0.23
La Decisa 33 cl single bottle	Primary packaging	33cl brown glass bottle - Giuggiaro Model	230.00

Product	Packaging type	Packaging components	Mass [g]
La Decisa 33 cl single bottle	Primary packaging	Tinplate crown cap	2.00
La Decisa 33 cl single bottle	Primary packaging	Two-sided labels and paper collar	0.50
La Decisa 33 cl single bottle	Primary packaging	Glue for labels	2.08
La Decisa 33 cl single bottle	Secondary packaging	Cardboard box for 24 bottles	10.42
La Decisa 33 cl single bottle	Secondary packaging	Glue for boxes	0.62
La Decisa 33 cl single bottle	Tertiary packaging	PE top cover	0.13
La Decisa 33 cl single bottle	Tertiary packaging	Pallet	13.2
La Decisa 33 cl single bottle	Tertiary packaging	Cardboard interlayer	0.66
La Decisa 33 cl single bottle	Tertiary packaging	Stretch film	0.23
La Decisa 33 cl in cluster	Primary packaging	33cl brown glass bottle - Giuggiaro Model	230.00
La Decisa 33 cl in cluster	Primary packaging	Tinplate crown cap	2.00
La Decisa 33 cl in cluster	Primary packaging	Two-sided labels and paper collar	0.50
La Decisa 33 cl in cluster	Primary packaging	Glue for labels	2.08
La Decisa 33 cl in cluster	Secondary packaging	Cardboard 3-bottles cluster	10.00
La Decisa 33 cl in cluster	Secondary packaging	Cardboard box for 24 bottles	10.42
La Decisa 33 cl in cluster	Secondary packaging	Glue for boxes	0.62
La Decisa 33 cl in cluster	Tertiary packaging	PE top cover	0.13
La Decisa 33 cl in cluster	Tertiary packaging	Pallet	13.2
La Decisa 33 cl in cluster	Tertiary packaging	Cardboard interlayer	0.66
La Decisa 33 cl in cluster	Tertiary packaging	Stretch film	0.23

As for the *glass bottles*: these have been accounted using the database Ecoinvent process of glass brown bottle production, considering the various processes such as: raw material and energy consumption, disposal of glass scrap, melting, bottle formation, cooling. The data set was appropriately adapted, using the Italian mix for the entire consumption of electricity. The glass bottles are delivered to the company transported on pallets and packaged with the following packaging: plastic interlayers, stretch film, cardboard top cover for which the raw material production and processing processes were considered using Ecoinvent database. The transport takes place on road from Italian suppliers and was accounted using the Ecoinvent database.

As for the *tinplate crown caps*, they were accounted from the cap production process. The tinplate is industrially produced using a sheet of steel and depositing on the surface a very fine layer of tin. The cap production, molding and tin deposition were accounted using Ecoinvent "steel", "metal working" and "tin plating, pieces" datasets. Tin-plated crown caps are delivered to the company in cardboard octabines and loaded on wooden pallets. The cardboard octabin and polyethylene bag to contain the caps during the transport were accounted using Ecoinvent database both for materials and for production processes. Finally, the transport of caps pallets was accounted using Ecoinvent database considering that both plants purchase caps from a single supplier located in Italy.

As for the *two-sided labels* and *paper collars*, they were accounted starting from the materials production. The following components were considered separately: front label, back label and collar. The paper used for these different components and the molding process were accounted described through the Ecoinvent database. Front labels, retro labels and collars are transported in cardboard trays wrapped in heat-shrink film in polyethylene. Trays contain a variable number of pieces depending on the delivered paper component; however, an average number of pieces of 18000/19000 units per tray was estimated. These cardboard trays were accounted using a specific Ecoinvent dataset for the raw material and for the production process as well as the plastic shrink film. The labels in packs are transported on pallets the palletizing scheme being very variable: an average load per pallet of 600 kg was estimated. Finally, the transport of the labels to the production facilities of San Giorgio di Nogaro and Pedavena was accounted using Ecoinvent database considering the only Italian supplier.

As for the *cardboard cluster*, it was accounted starting from the manufacturing process of the cardboard using the Ecoinvent database for the material and for the production process. Clusters are transported on wooden pallets containing, on average, 16250 units and are provided by a single supplier located in Italy. Pallets also have a shrink film that was accounted using Ecoinvent databases for material and extrusion process. The database Ecoinvent was also used to account the transport of cardboards. The clusters used for the Premium Beer are identical in terms of mass and material to those used for the La Decisa product, only a graphical change being made.

As for the *cardboard box*, it was accounted starting from the manufacturing process of the cardboard using the Ecoinvent database for material and production process. The San Giorgio di Nogaro factory purchases cardboard boxes from an exclusive supplier located in Italy. Boxes used in the case of the Premium beer have a different graphic and are different in terms of mass than those used for La Decisa.

As for the *glue* used to paste labels on bottles and to weld profiles of cardboard boxes and trays, it was accounted using Ecoinvent database. Packaging of this material was excluded because of the 1% cut-off criterion. Glue suppliers are located in Italy in the case of both production plants.

As for the polyethylene top cover used to cover finished product pallets, it was accounted using the Ecoinvent database for the material and for the extrusion process. The supplier of this material is located in Italy.

As for the *polyethylene stretch film* used to wrap finished product pallets, it was considered using a specific Ecoinvent datasets for the material and for the extrusion process. The supplier of this material is located in Italy. The company did not provide specific data on the mass used, but it was assumed that it was compatible with the one used to pack empty glass bottles entering the packaging process, for which primary data were available.

Cardboard interlayer was accounted using the Ecoinvent database.

Wooden pallets required for the distribution of the finished product and for the transportation of input materials, were accounted starting from the production using Ecoinvent database for material and production process. The San Giorgio factory buys pallets from a single supplier located in Italy: database Ecoinvent was used to account the transport. As the pallet is used for several production cycles, a pallet reuse factor of 20 times was assumed. With reference to the palletizing scheme, for the analyzed products was considered a factor of 1512 bottles per pallet of finished product.

The ink used for batch and product expiration date marking were excluded from accounting because they have a very low mass flow and therefore falling within the 1% cut-off threshold.

- ***Production process and beer packaging***. Plant energy consumption was allocated using total production data, this choice being reinforced by the fact that in the plant are produced beers of different type, so average energy consumption already takes into account this variability. The 2016 data on plant energy consumption, being global, includes both direct consumption items such as bottling line and packaging line as well as indirect energy consumption. The plant in San Giorgio di Nogaro has 3 natural gas boilers subservient to the production and a fuel-oil subservient to the heating of the offices and to the handling of the carriages. Emissions from boilers and electricity consumptions were accounted using Ecoinvent dataset appropriately modified by totally using the Italian mix. It should be noted that in relation to the production of electricity, a photovoltaic system was installed at the San Giorgio di Nogaro (UD) plant, which generated about 9.1% of electricity requirements in 2016: this system was accounted using specific Ecoinvent dataset.

  Another important aspect of the production process is the use of water. In the production process, water is used as a heat carrier for steam production and product component, the water content of the finished product being about 90. From the flow of water that enters the process, except for that contained in the beer, two outflows are generated: one is directed to a treatment plant and one is directly discharged into the surface body. The flow of wastewater was accounted using specific Ecoinvent dataset, as it has characteristics, in terms of polluting load, similar to those considered in this dataset, which in turn still refers to an agro-industrial production process. The remaining water flow, which represents most of the water, being used for thermal treatments or steam production, after thermal stabilization, is directly discharged into surface water as it has qualitative parameters that are compatible with the legislative limits.

The production process uses an ammonia refrigeration system for which losses were quantified and accounted as emissions to air. The other two refrigerant units with R-134A gas mixture required a certain amount of refilling at the end of 2016, the same quantity being considered as dispersed in the air.

During the process of alcoholic fermentation, moreover, CO_2 production is liquefied and used for washing the bottles before entering the beer, to get the air out of the empty bottle and to adjust the degree of carbonation of the finished product. The CO_2 produced during the alcoholic fermentation process is not enough to cover the total needs determined by these two uses and therefore it was necessary to purchase very modest amount of CO_2 units (less than 2%). As far as the production phase is concerned, the company provided an estimated value for CO_2 consumption for bottle washing, beer carbonation, and any safety relief. Finally, the production process generates waste flows resulting from the entry of the packaging. Moreover, in the packaging process, waste are produced consisting of glass, paper / board and tinplate. To account for the emissions of waste disposal processes, the end of life of these materials was designed, considering the disposal processes used at national level (ISPRA, 2015). The end-of-life scenarios considered are summarized in the Table 4.26.

Table 4.26. *Beverage industry products: materials end-of-life scenarios applied to the waste generated in the production process. Data source: ISPRA, 2015.*

Materials	Recycling scenario	Incineration scenario	Landfill scenario
Glass	72.9%	0.0%	27.1%
Cardboard	86.0%	7.2%	6.8%
Tinplate	73.6%	0.0%	26.4%
Plastic	38.6%	36.9%	24.5%
Wood	55.1%	2.7%	42.2%

To account for the various materials disposal processes, specific dataset of Ecoinvent database were used.

- ***Product distribution***. The distribution of Premium and La Decisa beers is carried out in the Italian market and is characterized by different weighted-average distances depending on the type of product and means of transport. The Table 4.27 summarizes the weighted-average distances for the distribution of the different products distinguishing the different types of means of transport used.

Table 4.27. *Beverage industry products: weighted-average distances for analyzed products distribution for different means of transport. Data for the Product "La Decisa cluster packaging" estimated based on business forecasts.*

Product	Means of transport	Distance [km]
Premium 33 cl single bottle	truck	486
Premium 33 cl single bottle	train	1100
Premium 33 cl single bottle	ship	2
Premium 33 cl in cluster	truck	470
Premium 33 cl in cluster	train	485
Premium 33 cl in cluster	ship	1
La Decisa 33 cl single bottle	truck	869
La Decisa 33 cl single bottle	train	0
La Decisa 33 cl single bottle	ship	1
La Decisa 33 cl in cluster	truck	470
La Decisa 33 cl in cluster	train	485
La Decisa 33 cl in cluster	ship	1

Ecoinvent database was used to account the transport processes. Another aspect considered in the distribution phase is related to the emissions from the energy consumption of the points of sale that were estimated through secondary data (Cecchinato *et al.*, 2010). Finally, emissions from the secondary and tertiary packaging disposal processes deriving from unpacking of the product were accounted using end of life scenarios based on data of ISPRA (2015).

- ***Product use phase***. The phase of use was accounted considering the transport of the purchased product to the consumer's home and the electricity consumed by the domestic refrigeration unit for cooling the product. The transport of the purchased product was accounted using a specific Ecoinvent dataset assimilated to a family car. The distance traveled was assumed to be 5 km as evidenced by a similar study (Point *et al.*, 2012). The aspect of the electricity consumed by the domestic refrigeration unit for cooling the product was assessed considering a refrigerator stay of 1 week, annual energy consumption of the refrigerator equal to 400 kWh, an occupied volume of the refrigerator of 144 liters (capacity 240 l, occupied at 60%) and a refrigerated product percentage of 70%. Energy consumption was then estimated, for each product, by diversifying the volumes occupied in the refrigerator. Finally, the disposal streams for secondary packaging were also considered in the use phase using end of life scenarios based on data of ISPRA (2015).
- ***Product end-of-life.*** The last considered downstream process corresponding to the last stage of the product life cycle was accounted considering the multi-component nature of the product, made

up of glass (bottle), paper (labels and collar, to which the adhesive fraction was mixed in very small mass) and tinplate (crown cap). The end of life of these materials was accounted distinguishing for each material three different types of disposal: recycling, incineration and disposal at landfills. The target percentages for individual disposal processes are in accordance with ISPRA report (ISPRA, 2015) as reported in the Table 4.28.

Table 4.28. *Beverage industru products: end-of-life scenarios applied to the product materials. Data source: ISPRA, 2015.*

Materials	Recycling scenario	Incineration scenario	Landfill scenario]
Glass	70.3%	0.0%	29.7%
Cardboard	79.5%	8.6%	11.8%
Tinplate	74.3%	0.0%	25.7%

To account for the various materials disposal processes, specific dataset of Ecoinvent database were used.

The impacts related to the human digestion process of beer and the treatment of the corresponding biological fluids were not considered as difficult to account for and presumably of very modest impact.

Starting from the modeling of inventory data described above and using the LCA software, the inventory results for the four product systems were calculated and then the nitrogen inventory results were determined by selecting the nitrogen-containing substances emissions. The nitrogen inventory results for the analyzed product systems are listed in the Table 4.29.

Table 4.29. *Nitrogen inventory results showing the emitted amount of nitrogen-containing substances in the various environmental compartments for the four analyzed product systems of the beverage industry.*

Substance	Comp.	Unit	Premium 33 s.b. Pedavena	Premium 33 clust. S.Giorgio	Decisa 33 s.b. S.Giorgio	Decisa 33 clust. S.Giorgio
2-Aminopropanol	Air	ng	2.17E+00	2.22E+00	2.13E+00	2.28E+00
2-Aminopropanol	Water	ng	5.20E+00	5.33E+00	5.11E+00	5.48E+00
2-Nitrobenzoic acid	Air	ng	4.83E+00	4.93E+00	4.81E+00	5.07E+00
Acephate	Air	ng	2.27E+00	3.16E+00	1.94E+00	3.16E+00
Acephate	Soil	ng	2.04E+01	2.65E+01	2.01E+01	2.65E+01
Acetamide	Air	pg	5.58E+02	7.77E+02	4.77E+02	7.78E+02
Acetamide	Soil	ng	2.90E+00	3.76E+00	2.86E+00	3.76E+00
Acetochlor	Soil	ng	2.43E+00	2.58E+00	2.58E+00	2.58E+00
Acetonitrile	Air	µg	1.25E+00	2.51E+00	1.21E+00	2.51E+00
Acetonitrile	Water	ng	4.92E+02	4.78E+02	4.94E+02	4.95E+02
Acifluorfen	Air	pg	3.11E+02	4.33E+02	2.66E+02	4.34E+02

Substance	Comp.	Unit	Premium 33 s.b. Pedavena	Premium 33 clust. S.Giorgio	Decisa 33 s.b. S.Giorgio	Decisa 33 clust. S.Giorgio
Acifluorfen	Soil	pg	1.33E+01	1.86E+01	1.14E+01	1.86E+01
Aclonifen	Soil	µg	8.07E-01	1.58E+00	8.07E-01	1.58E+00
Acrylonitrile	Water	pg	1.96E+02	1.92E+02	1.98E+02	1.98E+02
Alachlor	Air	ng	2.20E+00	3.07E+00	1.88E+00	3.07E+00
Alachlor	Soil	µg	8.90E+02	8.71E+02	9.01E+02	9.01E+02
Aldicarb	Soil	ng	6.83E+01	8.87E+01	6.72E+01	8.87E+01
Amidosulfuron	Soil	pg	1.23E+01	1.17E+01	1.13E+01	1.18E+01
Ammonia	Air	mg	1.61E+02	1.59E+02	1.62E+02	1.63E+02
Ammonia	Water	µg	2.92E+01	2.87E+01	2.96E+01	2.96E+01
Ammonia	Soil	µg	6.60E+01	6.47E+01	6.69E+01	6.69E+01
Ammonia, as N	Water	pg	1.26E+00	1.24E+00	1.28E+00	1.28E+00
Ammonium carbonate	Air	ng	1.96E+02	2.04E+02	1.94E+02	2.04E+02
Ammonium, ion	Air	pg	5.82E+01	5.71E+01	5.90E+01	5.90E+01
Ammonium, ion	Water	mg	1.78E+01	2.06E+01	1.67E+01	2.07E+01
Aniline	Air	ng	1.95E+01	2.47E+01	1.94E+01	2.51E+01
Aniline	Water	ng	4.69E+01	5.93E+01	4.67E+01	6.02E+01
Anthranilic acid	Air	ng	3.76E+00	3.83E+00	3.74E+00	3.94E+00
Asulam	Soil	pg	8.96E-01	9.57E-01	9.65E-01	9.59E-01
Atrazine	Air	ng	1.74E+00	2.43E+00	1.49E+00	2.43E+00
Atrazine	Soil	µg	4.56E+02	4.55E+02	4.61E+02	4.70E+02
Azoxystrobin	Air	ng	1.03E+00	1.43E+00	8.81E-01	1.43E+00
Azoxystrobin	Soil	ng	9.43E+02	9.17E+02	9.47E+02	9.48E+02
Benomyl	Soil	ng	2.75E+00	6.71E+00	2.79E+00	6.71E+00
Bentazone	Air	ng	9.52E-01	1.33E+00	8.14E-01	1.33E+00
Bentazone	Soil	ng	4.12E+02	8.04E+02	4.12E+02	8.04E+02
Benzene, 1-methyl-2-nitro-	Air	ng	4.17E+00	4.25E+00	4.15E+00	4.38E+00
Bifenox	Soil	ng	2.23E+02	2.16E+02	2.24E+02	2.24E+02
Bitertanol	Soil	ng	9.40E+01	9.13E+01	9.44E+01	9.44E+01
Bromoxynil	Soil	ng	5.60E+02	5.43E+02	5.62E+02	5.62E+02
Bromuconazole	Soil	pg	3.55E-04	3.38E-04	3.26E-04	3.38E-04
Carbaryl	Air	pg	2.60E+02	3.62E+02	2.22E+02	3.62E+02
Carbaryl	Soil	µg	6.12E+01	6.00E+01	6.20E+01	6.20E+01
Carbendazim	Soil	ng	3.63E+01	5.67E+01	3.32E+01	5.69E+01
Carbetamide	Soil	ng	5.43E+02	6.37E+02	4.69E+02	6.41E+02
Carbofuran	Soil	µg	1.51E+00	3.68E+00	1.53E+00	3.68E+00
Carfentrazone-ethyl	Air	pg	2.86E+01	3.98E+01	2.44E+01	3.98E+01
Carfentrazone-ethyl	Soil	ng	8.71E+00	8.45E+00	8.74E+00	8.74E+00
Chloramine	Air	ng	4.67E+01	4.99E+01	4.67E+01	5.12E+01
Chloramine	Water	ng	4.17E+02	4.46E+02	4.17E+02	4.57E+02
Chloridazon	Soil	pg	3.17E-02	3.01E-02	2.91E-02	3.02E-02
Chlorimuron-ethyl	Air	pg	5.20E+02	7.24E+02	4.44E+02	7.24E+02
Chlorimuron-ethyl	Soil	ng	1.24E+01	1.83E+01	1.08E+01	1.83E+01
Chlormequat	Soil	ng	4.51E+01	4.96E+01	4.30E+01	5.05E+01
Chlorothalonil	Soil	µg	5.43E+01	8.24E+01	5.44E+01	8.27E+01
Chlorpyrifos	Air	ng	1.04E+01	1.44E+01	8.87E+00	1.44E+01
Chlorpyrifos	Soil	µg	3.16E+01	3.10E+01	3.21E+01	3.21E+01
Chlorsulfuron	Soil	pg	4.89E-04	4.65E-04	4.49E-04	4.66E-04
Chlortoluron	Soil	mg	4.01E+00	3.89E+00	4.02E+00	4.02E+00

Substance	**Comp.**	**Unit**	**Premium 33 s.b. Pedavena**	**Premium 33 clust. S.Giorgio**	**Decisa 33 s.b. S.Giorgio**	**Decisa 33 clust. S.Giorgio**
Choline chloride	Soil	pg	6.74E-02	6.41E-02	6.19E-02	6.43E-02
Cinidon-ethyl	Soil	pg	1.49E+01	1.42E+01	1.37E+01	1.43E+01
Clethodim	Air	ng	1.54E+00	2.14E+00	1.31E+00	2.14E+00
Clethodim	Soil	ng	1.77E+01	2.61E+01	1.54E+01	2.61E+01
Clodinafop-propargyl	Soil	pg	7.24E-03	6.89E-03	6.65E-03	6.90E-03
Clomazone	Soil	ng	1.87E+01	2.54E+01	1.68E+01	2.55E+01
Clopyralid	Soil	ng	2.03E+01	1.99E+01	2.04E+01	2.06E+01
Cloquintocet-mexyl	Soil	pg	1.75E-03	1.66E-03	1.61E-03	1.67E-03
Cloransulam-methyl	Air	pg	2.71E+02	3.77E+02	2.31E+02	3.77E+02
Cloransulam-methyl	Soil	ng	5.31E+00	7.84E+00	4.64E+00	7.85E+00
Cyanide	Air	µg	4.64E+01	6.12E+01	4.29E+01	6.12E+01
Cyanide	Water	µg	6.59E+01	6.38E+01	6.17E+01	6.39E+01
Cyanoacetic acid	Air	ng	5.87E+02	5.71E+02	5.90E+02	5.91E+02
Cyfluthrin	Air	pg	5.43E+01	7.56E+01	4.64E+01	7.56E+01
Cyfluthrin	Soil	µg	2.09E+00	2.05E+00	2.12E+00	2.12E+00
Cyhalothrin	Soil	µg	3.44E+00	3.37E+00	3.49E+00	3.49E+00
Cyhalothrin, gamma-	Air	pg	6.23E+02	8.67E+02	5.32E+02	8.68E+02
Cyhalothrin, gamma-	Soil	pg	2.67E+01	3.72E+01	2.28E+01	3.72E+01
Cypermethrin	Air	pg	1.32E+02	1.83E+02	1.13E+02	1.83E+02
Cypermethrin	Soil	µg	2.93E+00	3.18E+00	2.96E+00	3.27E+00
Cyproconazole	Soil	µg	1.24E+01	1.20E+01	1.24E+01	1.24E+01
Cyprodinil	Soil	µg	5.17E+01	5.02E+01	5.19E+01	5.19E+01
Deltamethrin	Soil	ng	1.48E+01	1.47E+01	1.48E+01	1.51E+01
Diazinon	Soil	µg	2.06E+01	2.01E+01	2.08E+01	2.08E+01
Dicrotophos	Soil	ng	3.73E+00	4.84E+00	3.67E+00	4.84E+00
Diethylamine	Air	ng	9.23E+00	1.16E+01	9.16E+00	1.17E+01
Diethylamine	Water	ng	2.22E+01	2.77E+01	2.20E+01	2.82E+01
Difenoconazole	Soil	ng	1.63E+00	2.21E+00	1.46E+00	2.21E+00
Diflubenzuron	Air	pg	2.86E+01	3.98E+01	2.44E+01	3.98E+01
Diflubenzuron	Soil	µg	3.52E+00	5.20E+00	3.08E+00	5.20E+00
Diflufenican	Soil	µg	1.08E+00	1.05E+00	1.08E+00	1.08E+00
Diflufenzopyr-sodium	Soil	pg	7.88E+00	8.35E+00	8.35E+00	8.36E+00
Dimethachlor	Soil	ng	4.57E+01	6.20E+01	4.10E+01	6.23E+01
Dimethenamid	Soil	pg	5.60E+02	5.41E+02	5.32E+02	5.42E+02
Dimethoate	Soil	ng	1.28E+00	1.22E+00	1.18E+00	1.22E+00
Dimethylamine	Air	pg	5.95E+01	5.79E+01	5.67E+01	5.79E+01
Dimethylamine	Water	µg	3.63E+00	3.53E+00	3.64E+00	3.65E+00
Dinitrogen monoxide	Air	mg	5.43E+01	5.38E+01	5.40E+01	5.51E+01
Dipropylamine	Air	ng	4.66E+00	6.12E+00	4.64E+00	6.20E+00
Dipropylamine	Water	ng	1.12E+01	1.47E+01	1.11E+01	1.49E+01
Diquat	Soil	pg	2.24E+02	6.45E+02	2.31E+02	6.46E+02
Diquat dibromide	Soil	pg	1.45E-04	1.55E-04	1.56E-04	1.55E-04
Dithianone	Soil	pg	1.23E+02	1.17E+02	1.13E+02	1.18E+02
Diuron	Soil	ng	5.73E+00	7.44E+00	5.64E+00	7.44E+00
Epoxiconazole	Soil	ng	1.92E+02	1.87E+02	1.93E+02	1.93E+02
Esfenvalerate	Air	pg	3.25E+02	4.52E+02	2.77E+02	4.52E+02
Esfenvalerate	Soil	µg	9.39E+00	9.20E+00	9.51E+00	9.51E+00
Ethalfluralin	Soil	ng	1.52E+01	2.07E+01	1.37E+01	2.08E+01

Substance	Comp.	Unit	Premium 33 s.b. Pedavena	Premium 33 clust. S.Giorgio	Decisa 33 s.b. S.Giorgio	Decisa 33 clust. S.Giorgio
Ethylamine	Air	ng	1.42E+02	3.84E+02	1.42E+02	3.84E+02
Ethylamine	Water	ng	3.40E+02	9.22E+02	3.42E+02	9.23E+02
Ethylene diamine	Air	ng	2.26E+02	4.47E+02	2.27E+02	4.47E+02
Ethylene diamine	Water	µg	5.44E-01	1.07E+00	5.47E-01	1.07E+00
Fenbuconazole	Soil	pg	3.22E+01	3.07E+01	2.96E+01	3.07E+01
Fenoxaprop	Air	pg	4.25E+02	5.91E+02	3.63E+02	5.92E+02
Fenoxaprop	Soil	ng	1.06E+01	1.57E+01	9.27E+00	1.57E+01
Fenoxaprop-P ethyl ester	Soil	ng	6.47E+01	6.28E+01	6.49E+01	6.49E+01
Fenpiclonil	Soil	µg	1.78E+00	2.92E+00	1.78E+00	2.92E+00
Fenpropidin	Soil	µg	2.84E+00	2.76E+00	2.85E+00	2.85E+00
Fenpropimorph	Soil	µg	1.08E+01	1.05E+01	1.09E+01	1.09E+01
Fipronil	Soil	ng	2.23E+01	2.89E+01	2.19E+01	2.89E+01
Florasulam	Soil	ng	2.37E+01	2.30E+01	2.38E+01	2.38E+01
Fluazifop-p-butyl	Air	pg	6.10E+02	8.49E+02	5.21E+02	8.49E+02
Fluazifop-P-butyl	Soil	ng	1.48E+01	2.05E+01	1.32E+01	2.05E+01
Flucarbazone sodium salt	Soil	pg	3.06E-05	2.91E-05	2.81E-05	2.91E-05
Fludioxonil	Soil	ng	5.57E+01	5.41E+01	5.59E+01	5.59E+01
Flufenacet	Air	pg	2.29E+02	3.18E+02	1.95E+02	3.18E+02
Flufenacet	Soil	ng	9.47E+02	9.19E+02	9.50E+02	9.50E+02
Flumetsulam	Air	pg	5.35E+01	7.45E+01	4.57E+01	7.45E+01
Flumetsulam	Soil	pg	1.61E+01	1.78E+01	1.66E+01	1.78E+01
Flumiclorac-pentyl	Air	pg	9.15E+01	1.27E+02	7.82E+01	1.27E+02
Flumiclorac-pentyl	Soil	pg	3.92E+00	5.46E+00	3.35E+00	5.46E+00
Flumioxazin	Air	ng	9.26E-01	1.29E+00	7.91E-01	1.29E+00
Flumioxazin	Soil	ng	6.17E+00	9.11E+00	5.39E+00	9.11E+00
Fluroxypyr	Soil	ng	3.98E+01	3.87E+01	4.00E+01	4.00E+01
Flurtamone	Soil	ng	9.86E+02	9.58E+02	9.90E+02	9.90E+02
Flusilazole	Soil	ng	1.08E+02	1.05E+02	1.08E+02	1.08E+02
Fomesafen	Air	ng	3.44E+00	4.79E+00	2.94E+00	4.79E+00
Fomesafen	Soil	ng	4.06E+01	5.99E+01	3.55E+01	5.99E+01
Foramsulfuron	Soil	pg	1.48E+00	1.57E+00	1.57E+00	1.57E+00
Formamide	Air	ng	2.14E+01	2.30E+01	2.15E+01	2.36E+01
Formamide	Water	ng	5.14E+01	5.53E+01	5.15E+01	5.67E+01
Glyphosate	Air	ng	6.88E+02	9.58E+02	5.88E+02	9.58E+02
Glyphosate	Soil	µg	2.87E+02	2.78E+02	2.60E+02	2.86E+02
Imazamox	Air	pg	1.37E+02	1.91E+02	1.17E+02	1.91E+02
Imazamox	Soil	ng	5.31E+00	7.85E+00	4.65E+00	7.85E+00
Imazapyr	Soil	pg	1.97E-01	2.09E-01	2.09E-01	2.09E-01
Imazaquin	Air	pg	4.36E+02	6.08E+02	3.73E+02	6.08E+02
Imazaquin	Soil	pg	1.87E+01	2.60E+01	1.60E+01	2.61E+01
Imazethapyr	Air	ng	9.03E-01	1.26E+00	7.72E-01	1.26E+00
Imazethapyr	Soil	ng	1.33E+01	1.96E+01	1.16E+01	1.96E+01
Imidacloprid	Soil	ng	4.61E+02	4.54E+02	4.62E+02	4.69E+02
Indoxacarb	Soil	µg	3.43E+00	3.36E+00	3.48E+00	3.48E+00
Ioxynil	Soil	ng	3.36E+02	3.27E+02	3.38E+02	3.38E+02
Iprodione	Soil	ng	2.04E+01	2.77E+01	1.84E+01	2.79E+01
Isocyanic acid	Air	µg	1.04E+02	2.08E+02	1.02E+02	2.08E+02
Isopropylamine	Air	ng	4.85E+01	1.28E+02	4.87E+01	1.28E+02

Substance	**Comp.**	**Unit**	**Premium 33 s.b. Pedavena**	**Premium 33 clust. S.Giorgio**	**Decisa 33 s.b. S.Giorgio**	**Decisa 33 clust. S.Giorgio**
Isopropylamine	Water	ng	1.16E+02	3.08E+02	1.17E+02	3.08E+02
Isoproturon	Soil	mg	3.39E+00	3.29E+00	3.41E+00	3.41E+00
Isoxaflutole	Soil	pg	2.36E+01	2.50E+01	2.51E+01	2.51E+01
Kresoxim-methyl	Soil	ng	8.73E+00	8.47E+00	8.75E+00	8.76E+00
Lactofen	Air	pg	4.39E+02	6.12E+02	3.76E+02	6.12E+02
Lactofen	Soil	pg	1.88E+01	2.62E+01	1.61E+01	2.62E+01
Lambda-cyhalothrin	Soil	ng	1.12E+02	1.11E+02	1.12E+02	1.14E+02
Linuron	Soil	µg	7.35E+00	1.33E+01	7.24E+00	1.33E+01
Mancozeb	Soil	µg	5.78E+01	9.46E+01	5.79E+01	9.46E+01
Mefenpyr	Soil	ng	2.31E+02	2.24E+02	2.32E+02	2.32E+02
Mefenpyr-diethyl	Soil	ng	1.29E+02	1.26E+02	1.30E+02	1.30E+02
Mepiquat chloride	Soil	ng	9.13E+02	8.86E+02	9.16E+02	9.17E+02
Mesotrione	Soil	pg	6.40E+01	6.78E+01	6.79E+01	6.80E+01
Metamitron	Soil	pg	2.83E+02	3.01E+02	3.03E+02	3.02E+02
Metazachlor	Soil	µg	3.53E+01	3.46E+01	3.57E+01	3.58E+01
Methomyl	Soil	µg	9.86E+01	9.65E+01	9.98E+01	9.98E+01
Methylamine	Air	ng	1.84E+02	1.80E+02	1.85E+02	1.86E+02
Methylamine	Water	ng	4.42E+02	4.31E+02	4.44E+02	4.45E+02
Metolachlor	Air	ng	7.18E+00	1.00E+01	6.14E+00	1.00E+01
Metolachlor	Soil	mg	1.23E+00	1.26E+00	1.24E+00	1.30E+00
Metribuzin	Air	ng	2.85E+00	3.97E+00	2.44E+00	3.97E+00
Metribuzin	Soil	µg	2.08E+00	3.39E+00	2.08E+00	3.39E+00
Monocrotophos	Soil	ng	4.30E+02	6.35E+02	3.76E+02	6.36E+02
Monoethanolamine	Air	mg	3.66E+00	2.57E-01	1.06E-01	2.58E-01
Monoethanolamine	Water	ng	7.84E+00	7.04E+00	6.58E+00	7.05E+00
Napropamide	Soil	ng	3.62E+02	3.98E+02	3.08E+02	4.01E+02
Nitrate	Air	µg	9.92E+01	9.87E+01	1.16E+02	9.85E+01
Nitrate	Water	g	3.54E+00	3.66E+00	3.55E+00	3.75E+00
Nitrate	Soil	µg	1.81E+02	1.80E+02	2.16E+02	1.79E+02
Nitric oxide	Air	pg	2.45E+01	2.40E+01	2.48E+01	2.48E+01
Nitrite	Water	µg	5.86E+02	6.31E+02	5.29E+02	6.31E+02
Nitrobenzene	Air	ng	3.45E+01	4.13E+01	3.44E+01	4.21E+01
Nitrobenzene	Water	ng	1.38E+02	1.66E+02	1.38E+02	1.69E+02
Nitrogen	Air	mg	3.88E+00	3.78E+00	3.89E+00	3.90E+00
Nitrogen	Water	mg	9.42E+00	1.09E+01	8.96E+00	1.09E+01
Nitrogen	Soil	µg	1.96E+00	1.93E+00	2.07E+00	1.93E+00
Nitrogen dioxide	Air	mg	3.26E+00	3.20E+00	3.30E+00	3.30E+00
Nitrogen fluoride	Air	pg	1.42E-02	1.36E-02	1.42E-02	1.38E-02
Nitrogen oxides	Air	g	1.47E+00	1.42E+00	1.43E+00	1.42E+00
Nitrogen, organic bound	Water	mg	6.34E+00	7.31E+00	6.32E+00	7.31E+00
Nitrogen, total	Water	ng	1.24E+02	1.21E+02	1.25E+02	1.25E+02
Orbencarb	Soil	µg	1.10E+01	1.80E+01	1.10E+01	1.80E+01
Paraquat dichloride	Soil	µg	7.32E+00	7.17E+00	7.41E+00	7.41E+00
Parathion	Soil	ng	1.22E+00	1.29E+00	1.18E+00	1.31E+00
Particulates, <10µm	Air	µg	3.85E+02	3.77E+02	3.90E+02	3.90E+02
Particulates, <10µm	Water	ng	9.61E+00	9.41E+00	9.73E+00	9.73E+00
Particulates, <2.5µm	Air	mg	1.89E+02	1.83E+02	1.82E+02	1.83E+02
Particulates, >2.5 µm,< 10µm	Air	mg	8.89E+01	8.29E+01	8.73E+01	8.30E+01

Substance	Comp.	Unit	Premium 33 s.b. Pedavena	Premium 33 clust. S.Giorgio	Decisa 33 s.b. S.Giorgio	Decisa 33 clust. S.Giorgio
Pendimethalin	Air	ng	1.93E+01	2.69E+01	1.65E+01	2.69E+01
Pendimethalin	Soil	mg	2.76E+00	2.69E+00	2.78E+00	2.78E+00
Phenmedipham	Soil	pg	5.18E+01	5.51E+01	5.54E+01	5.52E+01
Propiconazole	Air	pg	3.37E+02	4.69E+02	2.88E+02	4.70E+02
Propiconazole	Soil	µg	1.07E+00	1.04E+00	1.07E+00	1.07E+00
Propylamine	Air	ng	2.08E+00	2.73E+00	2.08E+00	2.76E+00
Propylamine	Water	ng	4.99E+00	6.56E+00	4.98E+00	6.64E+00
Pyridate	Soil	µg	2.41E+02	2.36E+02	2.44E+02	2.44E+02
Simazine	Soil	pg	9.95E+01	1.05E+02	1.05E+02	1.06E+02
Sulfentrazone	Air	ng	2.19E+00	3.05E+00	1.88E+00	3.06E+00
Sulfentrazone	Soil	ng	6.37E+01	9.41E+01	5.58E+01	9.42E+01
t-Butylamine	Air	ng	4.56E+02	5.31E+02	4.57E+02	5.44E+02
t-Butylamine	Water	µg	1.09E+00	1.27E+00	1.10E+00	1.31E+00
Tebupirimphos	Soil	pg	4.14E+01	4.38E+01	4.39E+01	4.39E+01
Tebutam	Soil	µg	1.22E+00	1.20E+00	1.01E+00	1.22E+00
Terbuthylazin	Soil	µg	1.94E+02	1.90E+02	1.96E+02	1.96E+02
Tralkoxydim	Soil	µg	2.21E+00	2.14E+00	2.22E+00	2.22E+00
Trifloxystrobin	Air	pg	2.00E+01	2.78E+01	1.71E+01	2.79E+01
Trifloxystrobin	Soil	ng	1.28E+02	1.24E+02	1.28E+02	1.28E+02
Trifluralin	Air	ng	3.16E+01	4.40E+01	2.70E+01	4.40E+01
Trifluralin	Soil	ng	6.28E+02	8.41E+02	5.46E+02	8.43E+02
Trimethylamine	Air	ng	2.35E+00	2.39E+00	2.33E+00	2.46E+00
Trimethylamine	Water	ng	5.64E+00	5.72E+00	5.60E+00	5.89E+00
Urea	Water	ng	1.72E+01	2.17E+01	1.72E+01	2.20E+01

To calculate the nitrogen inventory results by selecting the nitrogen-containing substances, a mass cut-off criterion with an overall threshold set to 1 ng was applied, however including substances with fewer emissions considered to be particularly relevant due to potential environmental impacts.

4.4.3 Beverage industry products: assessment at inventory level

Starting from nitrogen inventory results and applying the calculated nitrogen coefficients, the reactive nitrogen results were accounted for all the emitted nitrogen-containing substances and then the reactive nitrogen indicator results were determined for the four analyzed product systems.

The results obtained are shown in the Table 4.30, in which the last row shows the total reactive nitrogen indicator value for each product system.

Table 4.30. *Reactive nitrogen results for the four analyzed product systems of the beverage industry. The reactive nitrogen indicator value for each product system is reported in the last row of the Table.*

Substance	**Comp.**	**Nitrog. coeff.**	**Reactive nitrogen results [kg/functional unit]**			
			Premium 33 s.b. Pedavena	**Premium 33 clust. S.Giorgio**	**Decisa 33 s.b. S.Giorgio**	**Decisa 33 clust. S.Giorgio**
2-Aminopropanol	Air	0.186	4.04E-13	4.13E-13	3.97E-13	4.25E-13
2-Aminopropanol	Water	0.186	9.70E-13	9.95E-13	9.54E-13	1.02E-12
2-Nitrobenzoic acid	Air	0.084	4.05E-13	4.13E-13	4.03E-13	4.25E-13
Acephate	Air	0.076	1.73E-13	2.41E-13	1.48E-13	2.41E-13
Acephate	Soil	0.076	1.56E-12	2.03E-12	1.53E-12	2.03E-12
Acetamide	Air	0.237	1.32E-13	1.84E-13	1.13E-13	1.84E-13
Acetamide	Soil	0.237	6.88E-13	8.91E-13	6.77E-13	8.91E-13
Acetochlor	Soil	0.052	1.26E-13	1.34E-13	1.34E-13	1.34E-13
Acetonitrile	Air	0.341	4.25E-10	8.58E-10	4.13E-10	8.58E-10
Acetonitrile	Water	0.341	1.68E-10	1.63E-10	1.69E-10	1.69E-10
Acifluorfen	Air	0.039	1.21E-14	1.68E-14	1.03E-14	1.68E-14
Acifluorfen	Soil	0.039	5.17E-16	7.19E-16	4.42E-16	7.20E-16
Aclonifen	Soil	0.106	8.54E-11	1.67E-10	8.55E-11	1.67E-10
Acrylonitrile	Water	0.264	5.17E-14	5.06E-14	5.23E-14	5.23E-14
Alachlor	Air	0.052	1.14E-13	1.59E-13	9.78E-14	1.59E-13
Alachlor	Soil	0.052	4.62E-08	4.52E-08	4.68E-08	4.68E-08
Aldicarb	Soil	0.147	1.01E-11	1.31E-11	9.90E-12	1.31E-11
Amidosulfuron	Soil	0.190	2.34E-15	2.23E-15	2.15E-15	2.23E-15
Ammonia	Air	0.822	1.32E-04	1.30E-04	1.33E-04	1.34E-04
Ammonia	Water	0.822	2.41E-08	2.36E-08	2.44E-08	2.44E-08
Ammonia	Soil	0.822	5.43E-08	5.32E-08	5.50E-08	5.50E-08
Ammonia, as N	Water	1.000	1.26E-15	1.24E-15	1.28E-15	1.28E-15
Ammonium carbonate	Air	0.292	5.71E-11	5.95E-11	5.64E-11	5.95E-11
Ammonium, ion	Air	0.776	4.52E-14	4.43E-14	4.58E-14	4.58E-14
Ammonium, ion	Water	0.776	1.38E-05	1.60E-05	1.30E-05	1.60E-05
Aniline	Air	0.150	2.93E-12	3.71E-12	2.92E-12	3.77E-12
Aniline	Water	0.150	7.05E-12	8.92E-12	7.02E-12	9.06E-12
Anthranilic acid	Air	0.102	3.84E-13	3.91E-13	3.82E-13	4.03E-13
Asulam	Soil	0.122	1.09E-16	1.16E-16	1.17E-16	1.17E-16
Atrazine	Air	0.325	5.66E-13	7.88E-13	4.84E-13	7.88E-13
Atrazine	Soil	0.325	1.48E-07	1.48E-07	1.50E-07	1.53E-07
Azoxystrobin	Air	0.104	1.07E-13	1.49E-13	9.17E-14	1.49E-13
Azoxystrobin	Soil	0.104	9.83E-11	9.56E-11	9.87E-11	9.88E-11
Benomyl	Soil	0.193	5.30E-13	1.29E-12	5.39E-13	1.30E-12
Bentazone	Air	0.117	1.11E-13	1.55E-13	9.49E-14	1.55E-13
Bentazone	Soil	0.117	4.81E-11	9.38E-11	4.81E-11	9.38E-11
Benzene, 1-methyl-2-nitro-	Air	0.102	4.26E-13	4.35E-13	4.24E-13	4.47E-13
Bifenox	Soil	0.041	9.13E-12	8.86E-12	9.16E-12	9.16E-12
Bitertanol	Soil	0.125	1.17E-11	1.14E-11	1.18E-11	1.18E-11
Bromoxynil	Soil	0.051	2.83E-11	2.75E-11	2.84E-11	2.84E-11
Bromuconazole	Soil	0.111	3.95E-20	3.76E-20	3.63E-20	3.77E-20
Carbaryl	Air	0.070	1.81E-14	2.52E-14	1.55E-14	2.52E-14
Carbaryl	Soil	0.070	4.26E-09	4.17E-09	4.32E-09	4.32E-09
Carbendazim	Soil	0.220	7.98E-12	1.25E-11	7.31E-12	1.25E-11

Substance	Comp.	Nitrog. coeff.	Reactive nitrogen results [kg/functional unit]			
			Premium 33 s.b. Pedavena	Premium 33 clust. S.Giorgio	Decisa 33 s.b. S.Giorgio	Decisa 33 clust. S.Giorgio
Carbetamide	Soil	0.119	6.44E-11	7.55E-11	5.56E-11	7.60E-11
Carbofuran	Soil	0.063	9.54E-11	2.33E-10	9.69E-11	2.33E-10
Carfentrazone-ethyl	Air	0.102	2.91E-15	4.05E-15	2.49E-15	4.06E-15
Carfentrazone-ethyl	Soil	0.102	8.87E-13	8.62E-13	8.91E-13	8.91E-13
Chloramine	Air	0.272	1.27E-11	1.36E-11	1.27E-11	1.39E-11
Chloramine	Water	0.272	1.13E-10	1.21E-10	1.13E-10	1.24E-10
Chloridazon	Soil	0.190	6.00E-18	5.71E-18	5.51E-18	5.72E-18
Chlorimuron-ethyl	Air	0.135	7.02E-14	9.77E-14	6.00E-14	9.78E-14
Chlorimuron-ethyl	Soil	0.135	1.67E-12	2.47E-12	1.46E-12	2.47E-12
Chlormequat	Soil	0.114	5.15E-12	5.67E-12	4.91E-12	5.76E-12
Chlorothalonil	Soil	0.105	5.72E-09	8.68E-09	5.73E-09	8.71E-09
Chlorpyrifos	Air	0.040	4.14E-13	5.77E-13	3.54E-13	5.77E-13
Chlorpyrifos	Soil	0.040	1.26E-09	1.24E-09	1.28E-09	1.28E-09
Chlorsulfuron	Soil	0.196	9.57E-20	9.11E-20	8.79E-20	9.12E-20
Chlortoluron	Soil	0.132	5.28E-07	5.12E-07	5.30E-07	5.30E-07
Choline chloride	Soil	0.100	6.76E-18	6.44E-18	6.21E-18	6.45E-18
Cinidon-ethyl	Soil	0.036	5.31E-16	5.06E-16	4.88E-16	5.06E-16
Clethodim	Air	0.039	5.98E-14	8.33E-14	5.12E-14	8.34E-14
Clethodim	Soil	0.039	6.87E-13	1.01E-12	6.01E-13	1.02E-12
Clodinafop-propargyl	Soil	0.040	2.90E-19	2.76E-19	2.66E-19	2.76E-19
Clomazone	Soil	0.058	1.09E-12	1.48E-12	9.82E-13	1.49E-12
Clopyralid	Soil	0.073	1.48E-12	1.45E-12	1.49E-12	1.50E-12
Cloquintocet-mexyl	Soil	0.042	7.29E-20	6.94E-20	6.70E-20	6.95E-20
Cloransulam-methyl	Air	0.163	4.41E-14	6.14E-14	3.77E-14	6.15E-14
Cloransulam-methyl	Soil	0.163	8.65E-13	1.28E-12	7.57E-13	1.28E-12
Cyanide	Air	0.538	2.50E-08	3.29E-08	2.31E-08	3.30E-08
Cyanide	Water	0.538	3.55E-08	3.43E-08	3.32E-08	3.44E-08
Cyanoacetic acid	Air	0.165	9.67E-11	9.41E-11	9.71E-11	9.72E-11
Cyfluthrin	Air	0.032	1.75E-15	2.44E-15	1.50E-15	2.44E-15
Cyfluthrin	Soil	0.032	6.74E-11	6.60E-11	6.83E-11	6.83E-11
Cyhalothrin	Soil	0.031	1.07E-10	1.05E-10	1.09E-10	1.09E-10
Cyhalothrin, gamma-	Air	0.031	1.94E-14	2.70E-14	1.66E-14	2.70E-14
Cyhalothrin, gamma-	Soil	0.031	8.31E-16	1.16E-15	7.11E-16	1.16E-15
Cypermethrin	Air	0.034	4.43E-15	6.17E-15	3.79E-15	6.17E-15
Cypermethrin	Soil	0.034	9.84E-11	1.07E-10	9.96E-11	1.10E-10
Cyproconazole	Soil	0.144	1.78E-09	1.73E-09	1.79E-09	1.79E-09
Cyprodinil	Soil	0.187	9.64E-09	9.36E-09	9.68E-09	9.68E-09
Deltamethrin	Soil	0.028	4.10E-13	4.07E-13	4.09E-13	4.20E-13
Diazinon	Soil	0.092	1.89E-09	1.85E-09	1.92E-09	1.92E-09
Dicrotophos	Soil	0.059	2.20E-13	2.86E-13	2.17E-13	2.86E-13
Diethylamine	Air	0.192	1.77E-12	2.21E-12	1.76E-12	2.25E-12
Diethylamine	Water	0.192	4.24E-12	5.31E-12	4.21E-12	5.39E-12
Difenoconazole	Soil	0.103	1.68E-13	2.28E-13	1.51E-13	2.29E-13
Diflubenzuron	Air	0.090	2.58E-15	3.59E-15	2.20E-15	3.59E-15
Diflubenzuron	Soil	0.090	3.17E-10	4.69E-10	2.78E-10	4.69E-10
Diflufenican	Soil	0.071	7.65E-11	7.43E-11	7.68E-11	7.68E-11
Diflufenzopyr-sodium	Soil	0.157	1.24E-15	1.31E-15	1.31E-15	1.32E-15

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Substance	**Comp.**	**Nitrog. coeff.**	**Reactive nitrogen results [kg/functional unit]**			
			Premium 33 s.b. Pedavena	**Premium 33 clust. S.Giorgio**	**Decisa 33 s.b. S.Giorgio**	**Decisa 33 clust. S.Giorgio**
Dimethachlor	Soil	0.055	2.50E-12	3.40E-12	2.25E-12	3.41E-12
Dimethenamid	Soil	0.051	2.84E-14	2.75E-14	2.70E-14	2.75E-14
Dimethoate	Soil	0.061	7.84E-14	7.46E-14	7.20E-14	7.47E-14
Dimethylamine	Air	0.311	1.85E-14	1.80E-14	1.76E-14	1.80E-14
Dimethylamine	Water	0.311	1.13E-09	1.10E-09	1.13E-09	1.14E-09
Dinitrogen monoxide	Air	0.636	3.46E-05	3.43E-05	3.44E-05	3.51E-05
Dipropylamine	Air	0.138	6.45E-13	8.47E-13	6.43E-13	8.58E-13
Dipropylamine	Water	0.138	1.55E-12	2.03E-12	1.54E-12	2.06E-12
Diquat	Soil	0.152	3.41E-14	9.81E-14	3.50E-14	9.82E-14
Diquat dibromide	Soil	0.081	1.18E-20	1.26E-20	1.27E-20	1.26E-20
Dithianone	Soil	0.095	1.17E-14	1.11E-14	1.07E-14	1.11E-14
Diuron	Soil	0.120	6.89E-13	8.94E-13	6.78E-13	8.94E-13
Epoxiconazole	Soil	0.127	2.45E-11	2.38E-11	2.46E-11	2.46E-11
Esfenvalerate	Air	0.033	1.08E-14	1.51E-14	9.26E-15	1.51E-14
Esfenvalerate	Soil	0.033	3.13E-10	3.07E-10	3.17E-10	3.17E-10
Ethalfluralin	Soil	0.126	1.92E-12	2.61E-12	1.72E-12	2.62E-12
Ethylamine	Air	0.311	4.40E-11	1.19E-10	4.43E-11	1.19E-10
Ethylamine	Water	0.311	1.06E-10	2.86E-10	1.06E-10	2.87E-10
Ethylene diamine	Air	0.466	1.05E-10	2.08E-10	1.06E-10	2.08E-10
Ethylene diamine	Water	0.466	2.54E-10	5.00E-10	2.55E-10	5.01E-10
Fenbuconazole	Soil	0.166	5.36E-15	5.10E-15	4.93E-15	5.11E-15
Fenoxaprop	Air	0.042	1.78E-14	2.48E-14	1.52E-14	2.48E-14
Fenoxaprop	Soil	0.042	4.45E-13	6.57E-13	3.89E-13	6.58E-13
Fenoxaprop-P ethyl ester	Soil	0.039	2.50E-12	2.43E-12	2.51E-12	2.51E-12
Fenpiclonil	Soil	0.118	2.10E-10	3.45E-10	2.11E-10	3.45E-10
Fenpropidin	Soil	0.051	1.45E-10	1.41E-10	1.46E-10	1.46E-10
Fenpropimorph	Soil	0.046	5.00E-10	4.85E-10	5.02E-10	5.02E-10
Fipronil	Soil	0.128	2.86E-12	3.71E-12	2.81E-12	3.71E-12
Florasulam	Soil	0.195	4.61E-12	4.48E-12	4.63E-12	4.63E-12
Fluazifop-p-butyl	Air	0.037	2.23E-14	3.10E-14	1.90E-14	3.10E-14
Fluazifop-P-butyl	Soil	0.037	5.40E-13	7.48E-13	4.82E-13	7.51E-13
Flucarbazone sodium salt	Soil	0.134	4.09E-21	3.90E-21	3.76E-21	3.90E-21
Fludioxonil	Soil	0.113	6.29E-12	6.11E-12	6.31E-12	6.31E-12
Flufenacet	Air	0.116	2.64E-14	3.68E-14	2.26E-14	3.68E-14
Flufenacet	Soil	0.116	1.09E-10	1.06E-10	1.10E-10	1.10E-10
Flumetsulam	Air	0.215	1.15E-14	1.60E-14	9.84E-15	1.60E-14
Flumetsulam	Soil	0.215	3.46E-15	3.83E-15	3.57E-15	3.84E-15
Flumiclorac-pentyl	Air	0.033	3.02E-15	4.21E-15	2.59E-15	4.21E-15
Flumiclorac-pentyl	Soil	0.033	1.30E-16	1.80E-16	1.11E-16	1.81E-16
Flumioxazin	Air	0.079	7.32E-14	1.02E-13	6.26E-14	1.02E-13
Flumioxazin	Soil	0.079	4.87E-13	7.20E-13	4.26E-13	7.20E-13
Fluroxypyr	Soil	0.110	4.38E-12	4.25E-12	4.39E-12	4.39E-12
Flurtamone	Soil	0.042	4.15E-11	4.03E-11	4.16E-11	4.16E-11
Flusilazole	Soil	0.133	1.44E-11	1.39E-11	1.44E-11	1.44E-11
Fomesafen	Air	0.064	2.20E-13	3.06E-13	1.88E-13	3.06E-13
Fomesafen	Soil	0.064	2.59E-12	3.82E-12	2.27E-12	3.83E-12
Foramsulfuron	Soil	0.186	2.75E-16	2.91E-16	2.91E-16	2.91E-16

			Reactive nitrogen results [kg/functional unit]			
Substance	**Comp.**	**Nitrog. coeff.**	**Premium 33 s.b. Pedavena**	**Premium 33 clust. S.Giorgio**	**Decisa 33 s.b. S.Giorgio**	**Decisa 33 clust. S.Giorgio**
Formamide	Air	0.311	6.66E-12	7.16E-12	6.67E-12	7.35E-12
Formamide	Water	0.311	1.60E-11	1.72E-11	1.60E-11	1.76E-11
Glyphosate	Air	0.083	5.70E-11	7.93E-11	4.87E-11	7.94E-11
Glyphosate	Soil	0.083	2.38E-08	2.30E-08	2.15E-08	2.37E-08
Imazamox	Air	0.138	1.88E-14	2.62E-14	1.61E-14	2.62E-14
Imazamox	Soil	0.138	7.31E-13	1.08E-12	6.40E-13	1.08E-12
Imazapyr	Soil	0.161	3.17E-17	3.36E-17	3.36E-17	3.36E-17
Imazaquin	Air	0.135	5.89E-14	8.20E-14	5.04E-14	8.21E-14
Imazaquin	Soil	0.135	2.52E-15	3.51E-15	2.16E-15	3.52E-15
Imazethapyr	Air	0.145	1.31E-13	1.83E-13	1.12E-13	1.83E-13
Imazethapyr	Soil	0.145	1.92E-12	2.84E-12	1.68E-12	2.85E-12
Imidacloprid	Soil	0.274	1.26E-10	1.24E-10	1.27E-10	1.28E-10
Indoxacarb	Soil	0.080	2.73E-10	2.68E-10	2.77E-10	2.77E-10
Ioxynil	Soil	0.038	1.27E-11	1.23E-11	1.28E-11	1.28E-11
Iprodione	Soil	0.127	2.60E-12	3.53E-12	2.34E-12	3.55E-12
Isocyanic acid	Air	0.326	3.40E-08	6.78E-08	3.32E-08	6.78E-08
Isopropylamine	Air	0.237	1.15E-11	3.04E-11	1.15E-11	3.04E-11
Isopropylamine	Water	0.237	2.76E-11	7.29E-11	2.77E-11	7.29E-11
Isoproturon	Soil	0.136	4.61E-07	4.47E-07	4.63E-07	4.63E-07
Isoxaflutole	Soil	0.039	9.22E-16	9.76E-16	9.77E-16	9.78E-16
Kresoxim-methyl	Soil	0.045	3.90E-13	3.79E-13	3.91E-13	3.91E-13
Lactofen	Air	0.030	1.33E-14	1.86E-14	1.14E-14	1.86E-14
Lactofen	Soil	0.030	5.71E-16	7.95E-16	4.88E-16	7.96E-16
Lambda-cyhalothrin	Soil	0.031	3.50E-12	3.45E-12	3.50E-12	3.56E-12
Linuron	Soil	0.112	8.27E-10	1.50E-09	8.14E-10	1.50E-09
Mancozeb	Soil	0.104	5.98E-09	9.80E-09	6.00E-09	9.80E-09
Mefenpyr	Soil	0.088	2.04E-11	1.98E-11	2.05E-11	2.05E-11
Mefenpyr-diethyl	Soil	0.075	9.71E-12	9.43E-12	9.75E-12	9.75E-12
Mepiquat chloride	Soil	0.094	8.54E-11	8.30E-11	8.58E-11	8.58E-11
Mesotrione	Soil	0.041	2.64E-15	2.80E-15	2.80E-15	2.81E-15
Metamitron	Soil	0.277	7.83E-14	8.34E-14	8.39E-14	8.35E-14
Metazachlor	Soil	0.151	5.34E-09	5.24E-09	5.41E-09	5.42E-09
Methomyl	Soil	0.173	1.70E-08	1.67E-08	1.72E-08	1.72E-08
Methylamine	Air	0.451	8.31E-11	8.10E-11	8.34E-11	8.37E-11
Methylamine	Water	0.451	1.99E-10	1.94E-10	2.00E-10	2.01E-10
Metolachlor	Air	0.049	3.54E-13	4.94E-13	3.03E-13	4.94E-13
Metolachlor	Soil	0.049	6.06E-08	6.20E-08	6.14E-08	6.39E-08
Metribuzin	Air	0.261	7.45E-13	1.04E-12	6.37E-13	1.04E-12
Metribuzin	Soil	0.261	5.43E-10	8.87E-10	5.43E-10	8.87E-10
Monocrotophos	Soil	0.063	2.70E-11	3.99E-11	2.36E-11	3.99E-11
Monoethanolamine	Air	0.229	8.40E-07	5.90E-08	2.44E-08	5.91E-08
Monoethanolamine	Water	0.229	1.80E-12	1.61E-12	1.51E-12	1.62E-12
Napropamide	Soil	0.052	1.87E-11	2.05E-11	1.59E-11	2.07E-11
Nitrate	Air	0.226	2.24E-08	2.23E-08	2.63E-08	2.23E-08
Nitrate	Water	0.226	8.00E-04	8.28E-04	8.01E-04	8.46E-04
Nitrate	Soil	0.226	4.09E-08	4.06E-08	4.89E-08	4.05E-08
Nitric oxide	Air	0.467	1.14E-14	1.12E-14	1.16E-14	1.16E-14

			Reactive nitrogen results [kg/functional unit]			
Substance	**Comp.**	**Nitrog. coeff.**	**Premium 33 s.b. Pedavena**	**Premium 33 clust. S.Giorgio**	**Decisa 33 s.b. S.Giorgio**	**Decisa 33 clust. S.Giorgio**
Nitrite	Water	0.304	1.78E-07	1.92E-07	1.61E-07	1.92E-07
Nitrobenzene	Air	0.114	3.92E-12	4.70E-12	3.91E-12	4.79E-12
Nitrobenzene	Water	0.114	1.57E-11	1.88E-11	1.57E-11	1.92E-11
Nitrogen	Air	0.000	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Nitrogen	Water	1.000	9.42E-06	1.09E-05	8.96E-06	1.09E-05
Nitrogen	Soil	1.000	1.96E-09	1.93E-09	2.07E-09	1.93E-09
Nitrogen dioxide	Air	0.304	9.93E-07	9.73E-07	1.01E-06	1.01E-06
Nitrogen fluoride	Air	0.197	2.80E-18	2.69E-18	2.80E-18	2.73E-18
Nitrogen oxides	Air	0.304	4.47E-04	4.33E-04	4.35E-04	4.33E-04
Nitrogen, organic bound	Water	0.160	1.01E-06	1.17E-06	1.01E-06	1.17E-06
Nitrogen, total	Water	1.000	1.24E-10	1.21E-10	1.25E-10	1.25E-10
Orbencarb	Soil	0.054	5.97E-10	9.77E-10	5.98E-10	9.77E-10
Paraquat dichloride	Soil	0.109	7.97E-10	7.81E-10	8.07E-10	8.07E-10
Parathion	Soil	0.048	5.85E-14	6.20E-14	5.67E-14	6.28E-14
Particulates, <10μm	Air	0.054	2.09E-08	2.04E-08	2.11E-08	2.11E-08
Particulates, <10μm	Water	0.054	5.21E-13	5.11E-13	5.28E-13	5.28E-13
Particulates, <2.5μm	Air	0.081	1.52E-05	1.47E-05	1.47E-05	1.47E-05
Particulates, >2.5 μm,< 10μm	Air	0.028	2.48E-06	2.31E-06	2.44E-06	2.32E-06
Pendimethalin	Air	0.149	2.89E-12	4.02E-12	2.47E-12	4.02E-12
Pendimethalin	Soil	0.149	4.13E-07	4.01E-07	4.15E-07	4.15E-07
Phenmedipham	Soil	0.093	4.83E-15	5.14E-15	5.17E-15	5.15E-15
Propiconazole	Air	0.123	4.14E-14	5.76E-14	3.54E-14	5.77E-14
Propiconazole	Soil	0.123	1.31E-10	1.27E-10	1.31E-10	1.31E-10
Propylamine	Air	0.237	4.93E-13	6.47E-13	4.92E-13	6.55E-13
Propylamine	Water	0.237	1.18E-12	1.55E-12	1.18E-12	1.57E-12
Pyridate	Soil	0.074	1.78E-08	1.75E-08	1.81E-08	1.81E-08
Simazine	Soil	0.347	3.46E-14	3.66E-14	3.66E-14	3.67E-14
Sulfentrazone	Air	0.145	3.17E-13	4.42E-13	2.71E-13	4.42E-13
Sulfentrazone	Soil	0.145	9.22E-12	1.36E-11	8.07E-12	1.36E-11
t-Butylamine	Air	0.192	8.72E-11	1.02E-10	8.76E-11	1.04E-10
t-Butylamine	Water	0.192	2.09E-10	2.44E-10	2.10E-10	2.50E-10
Tebupirimphos	Soil	0.088	3.64E-15	3.86E-15	3.86E-15	3.86E-15
Tebutam	Soil	0.060	7.31E-11	7.23E-11	6.07E-11	7.29E-11
Terbuthylazin	Soil	0.305	5.90E-08	5.78E-08	5.98E-08	5.98E-08
Tralkoxydim	Soil	0.043	9.39E-11	9.12E-11	9.43E-11	9.43E-11
Trifloxystrobin	Air	0.069	1.37E-15	1.91E-15	1.17E-15	1.91E-15
Trifloxystrobin	Soil	0.069	8.76E-12	8.51E-12	8.80E-12	8.80E-12
Trifluralin	Air	0.125	3.96E-12	5.51E-12	3.38E-12	5.52E-12
Trifluralin	Soil	0.125	7.87E-11	1.05E-10	6.84E-11	1.06E-10
Trimethylamine	Air	0.237	5.56E-13	5.65E-13	5.53E-13	5.82E-13
Trimethylamine	Water	0.237	1.34E-12	1.36E-12	1.33E-12	1.40E-12
Urea	Water	0.466	8.03E-12	1.01E-11	8.01E-12	1.03E-11
Total (product systems reactive nitrogen indicator)			**1.46E-03**	**1.47E-03**	**1.45E-03**	**1.50E-03**

Results obtained are very similar for the four product systems, to further confirmation of the strong analogies between the analyzed products, as already highlighted in the description of the life cycle phases. With regard to the “La Decisa” product, it should be noted, as expected, a greater impact for the product packed in cluster, due to the additional packaging used; the same consideration can not be directly extended to the “Premium” product as the two systems analyzed for this product are obtained in two different industrial plants.

Also in this case, the greatest contribution to the total reactive nitrogen calculated for the product systems is attributable to emissions of nitrate, nitrogen oxides, ammonia and dinitrogen monoxide as shown in the Table 4.31.

Table 4.31. *Main substances contribution [%] to reactive nitrogen indicator for the four analyzed product systems of the beverage industry.*

Substance	Comp.	Premium 33 s.b. Pedavena	Premium 33 clust. S.Giorgio	Decisa 33 s.b. S.Giorgio	Decisa 33 clust. S.Giorgio
Ammonia	Air	9.1%	8.9%	9.2%	9.0%
Dinitrogen monoxide	Air	2.4%	2.3%	2.4%	2.3%
Nitrate	Water	54.8%	56.2%	55.4%	56.5%
Nitrogen oxides	Air	30.6%	29.4%	30.1%	28.9%

Even in the case of this specific result, the strong analogy between the analyzed product systems is noteworthy.

It was also found a lower percentage contribution of nitrate emissions compared to the previous applications, probably due to the accounting of industrial processes that, compared to more specifically agricultural processes, shift the contribution towards emissions of different nature.

The reactive nitrogen indicator results [g/functional unit] and the main substances contribution are also graphically represented in the Figure 4.9 in order to provide a further example of results output format obtained by applying the methodology.

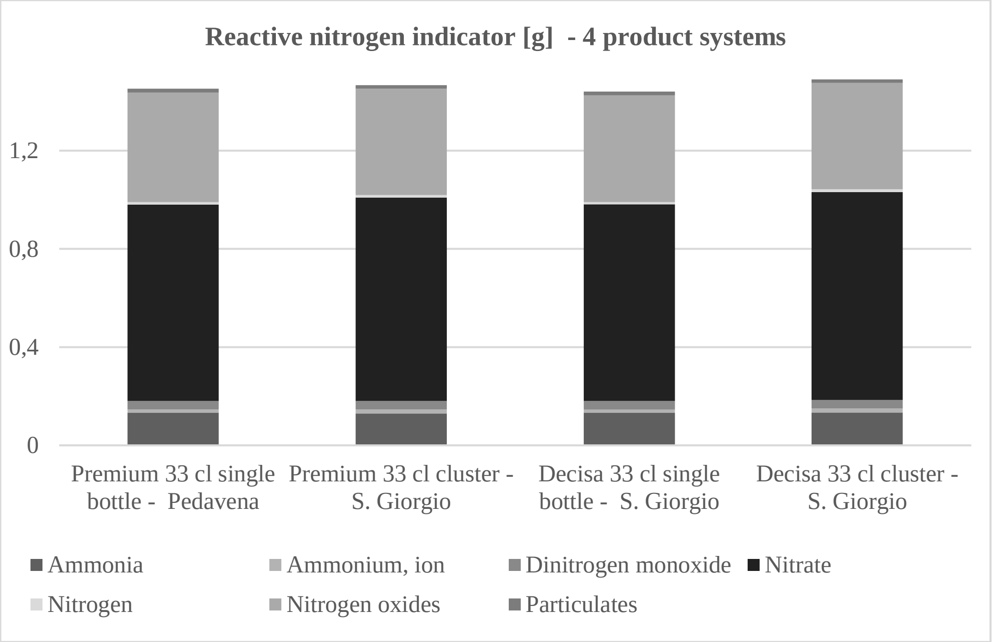


Figure 4.9. *Reactive nitrogen indicator results for the four analyzed product systems of the beverage industry showing output substances contribution (percentage >1%).*

While not being the direct comparison between the four product systems one of the objectives of this application, in the hypothetical ranking, with regard to the results in terms of reactive nitrogen indicator, the “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant” resulted in a lower impact, followed by the “Premium 33 cl single bottle – Pedavena plant” product, after by the “Premium 33 cl cluster packaging – S. Giorgio di Nogaro plant” product and finally by the “La Decisa 33 cl cluster packaging – S. Giorgio di Nogaro plant” product. This hypothetical ranking is highlighted as considered useful for subsequent analysis of results.

4.4.4 Beverage industry products: characterization

Starting from the nitrogen inventory results, the calculation of nitrogen impact assessment profile was performed. This consists of the union of the category indicator results for the nine selected impact categories, obtained by applying the characterization factors to the nitrogen-containing substances. The results obtained for the four analyzed product systems are reported into two different Tables to allow reading: Table 4.32 for single bottle products and Table 4.33 for cluster-packaged products. The nitrogen-containing substance for which characterization factors are defined by the models used are listed for each impact category. For simplicity of calculation a cut-off criterion was applied, limited to the impact categories freshwater ecotoxicity, human toxicity cancer effect and human toxicity non cancer effect, excluding the substances which made a contribution of less than 0.1% to the total impact of each category.

Table 4.32. *Nitrogen impact assessment profile calculated for products "Premium 33 cl single bottle" and "La Decisa 33 cl single bottle". Cut-off criterion of 0.1% applied to the categories Freshwater ecotoxicity, Human toxicity cancer effect and Human toxicity non-cancer effect.*

Impact category	**Substance**	**Comp.**	**Unit**	**Premium 33 s.b. Pedavena**	**Decisa 33 s.b. S.Giorgio**
Climate change	Dinitrog. monoxide	Air	kg CO_2 eq	1.44E-02	1.43E-02
Climate change	Nitrogen fluoride	Air	kg CO_2 eq	2.28E-13	2.28E-13
Climate change	**Total**		**kg CO_2 eq**	**1.44E-02**	**1.43E-02**
Particulate matter	Ammonia	Air	kg $PM_{2.5}$ eq	1.07E-05	1.08E-05
Particulate matter	Nitric oxide	Air	kg $PM_{2.5}$ eq	2.72E-16	2.75E-16
Particulate matter	Nitrogen dioxide	Air	kg $PM_{2.5}$ eq	2.35E-08	2.39E-08
Particulate matter	Nitrogen oxides	Air	kg $PM_{2.5}$ eq	1.10E-05	1.07E-05
Particulate matter	Particul. <10µm	Air	kg $PM_{2.5}$ eq	8.77E-08	8.89E-08
Particulate matter	Particul. <2.5µm	Air	kg $PM_{2.5}$ eq	3.48E-04	3.44E-04
Particulate matter	**Total**		**kg $PM_{2.5}$ eq**	**3.70E-04**	**3.65E-04**
Photoch. ozone form.	Nitric oxide	Air	kg NMVOC eq	2.45E-14	2.48E-14
Photoch. ozone form.	Nitrogen dioxide	Air	kg NMVOC eq	3.26E-06	3.30E-06
Photoch. ozone form.	Nitrogen oxides	Air	kg NMVOC eq	1.47E-03	1.43E-03
Photoch. ozone form.	**Total**		**kg NMVOC eq**	**1.47E-03**	**1.43E-03**
Acidification	Ammonia	Air	molc H^+ eq	4.86E-04	4.88E-04
Acidification	Nitric oxide	Air	molc H^+ eq	2.77E-14	2.80E-14
Acidification	Nitrogen dioxide	Air	molc H^+ eq	2.41E-06	2.45E-06
Acidification	Nitrogen oxides	Air	molc H^+ eq	1.09E-03	1.06E-03
Acidification	**Total**		**molc H^+ eq**	**1.57E-03**	**1.55E-03**
Terrestrial eutrophication	Ammonia	Air	molc N eq	2.17E-03	2.18E-03
Terrestrial eutrophication	Ammonium, ion	Air	molc N eq	7.40E-13	7.49E-13
Terrestrial eutrophication	Nitrate	Air	molc N eq	3.13E-07	3.67E-07
Terrestrial eutrophication	Nitric oxide	Air	molc N eq	1.60E-13	1.62E-13
Terrestrial eutrophication	Nitrogen dioxide	Air	molc N eq	1.39E-05	1.41E-05
Terrestrial eutrophication	Nitrogen oxides	Air	molc N eq	6.25E-03	6.09E-03
Terrestrial eutrophication	**Total**		**molc N eq**	**8.43E-03**	**8.29E-03**
Marine eutrophication	Ammonia	Air	kg N eq	1.48E-05	1.49E-05
Marine eutrophication	Ammonia	Water	kg N eq	2.41E-08	2.44E-08
Marine eutrophication	Ammonium, ion	Air	kg N eq	5.07E-15	5.13E-15
Marine eutrophication	Ammonium, ion	Water	kg N eq	1.38E-05	1.30E-05
Marine eutrophication	Nitrate	Air	kg N eq	2.78E-09	3.25E-09
Marine eutrophication	Nitrate	Water	kg N eq	8.00E-04	8.01E-04
Marine eutrophication	Nitric oxide	Air	kg N eq	1.46E-14	1.48E-14
Marine eutrophication	Nitrite	Water	kg N eq	1.78E-07	1.61E-07
Marine eutrophication	Nitrogen dioxide	Air	kg N eq	1.27E-06	1.29E-06
Marine eutrophication	Nitrogen oxides	Air	kg N eq	5.71E-04	5.56E-04
Marine eutrophication	Nitrogen, total	Water	kg N eq	1.24E-10	1.25E-10
Marine eutrophication	**Total**		**kg N eq**	**1.40E-03**	**1.39E-03**
Freshwater ecotoxicity	Alachlor	Soil	CTUe	8.25E-03	8.36E-03
Freshwater ecotoxicity	Atrazine	Soil	CTUe	5.19E-03	5.26E-03

Impact category	**Substance**	**Comp.**	**Unit**	**Premium 33 s.b. Pedavena**	**Decisa 33 s.b. S.Giorgio**
Freshwater ecotoxicity	Chlorothalonil	Soil	CTUe	3.14E-03	3.15E-03
Freshwater ecotoxicity	Chlorpyrifos	Soil	CTUe	3.35E-03	3.40E-03
Freshwater ecotoxicity	Isoproturon	Soil	CTUe	3.21E-02	3.22E-02
Freshwater ecotoxicity	Metolachlor	Soil	CTUe	7.32E-03	7.41E-03
Freshwater ecotoxicity	Pendimethalin	Soil	CTUe	8.10E-03	8.14E-03
Freshwater ecotoxicity	Terbuthylazin	Soil	CTUe	1.04E-02	1.05E-02
Freshwater ecotoxicity	**Total**		**CTUe**	**7.78E-02**	**7.84E-02**
Human tox. canc. eff.	**Total**		**CTUh**	**0.00E+00**	**0.00E+00**
Human tox. non-canc. eff.	**Total**		**CTUh**	**0.00E+00**	**0.00E+00**

Table 4.33. *Nitrogen impact assessment profile calculated for products "Premium 33 cl cluster packaging" and "La Decisa 33 cl cluster packaging". Cut-off criterion of 0.1% applied to the categories Freshwater ecotoxicity, Human toxicity cancer effect and Human toxicity non-cancer effect.*

Impact category	**Substance**	**Comp.**	**Unit**	**Premium 33 clust. S.Giorgio**	**Decisa 33 clust. S.Giorgio**
Climate change	Dinitrog. monoxide	Air	kg CO_2 eq	1.43E-02	1.46E-02
Climate change	Nitrogen fluoride	Air	kg CO_2 eq	2.19E-13	2.22E-13
Climate change	**Total**		**kg CO_2 eq**	**1.43E-02**	**1.46E-02**
Particulate matter	Ammonia	Air	kg $PM_{2.5}$ eq	1.06E-05	1.09E-05
Particulate matter	Nitric oxide	Air	kg $PM_{2.5}$ eq	2.66E-16	2.75E-16
Particulate matter	Nitrogen dioxide	Air	kg $PM_{2.5}$ eq	2.31E-08	2.39E-08
Particulate matter	Nitrogen oxides	Air	kg $PM_{2.5}$ eq	1.07E-05	1.07E-05
Particulate matter	Particul. <10µm	Air	kg $PM_{2.5}$ eq	8.59E-08	8.89E-08
Particulate matter	Particul. <2.5µm	Air	kg $PM_{2.5}$ eq	3.46E-04	3.47E-04
Particulate matter	**Total**		**kg $PM_{2.5}$ eq**	**3.68E-04**	**3.68E-04**
Photoch. ozone form.	Nitric oxide	Air	kg NMVOC eq	2.40E-14	2.48E-14
Photoch. ozone form.	Nitrogen dioxide	Air	kg NMVOC eq	3.20E-06	3.30E-06
Photoch. ozone form.	Nitrogen oxides	Air	kg NMVOC eq	1.42E-03	1.42E-03
Photoch. ozone form.	**Total**		**kg NMVOC eq**	**1.42E-03**	**1.43E-03**
Acidification	Ammonia	Air	molc H^+ eq	4.79E-04	4.92E-04
Acidification	Nitric oxide	Air	molc H^+ eq	2.71E-14	2.80E-14
Acidification	Nitrogen dioxide	Air	molc H^+ eq	2.36E-06	2.45E-06
Acidification	Nitrogen oxides	Air	molc H^+ eq	1.05E-03	1.05E-03
Acidification	**Total**		**molc H^+ eq**	**1.53E-03**	**1.55E-03**
Terrestrial eutrophication	Ammonia	Air	molc N eq	2.14E-03	2.20E-03
Terrestrial eutrophication	Ammonium, ion	Air	molc N eq	7.25E-13	7.49E-13
Terrestrial eutrophication	Nitrate	Air	molc N eq	3.12E-07	3.11E-07
Terrestrial eutrophication	Nitric oxide	Air	molc N eq	1.57E-13	1.62E-13
Terrestrial eutrophication	Nitrogen dioxide	Air	molc N eq	1.36E-05	1.41E-05
Terrestrial eutrophication	Nitrogen oxides	Air	molc N eq	6.05E-03	6.07E-03
Terrestrial eutrophication	**Total**		**molc N eq**	**8.21E-03**	**8.28E-03**
Marine eutrophication	Ammonia	Air	kg N eq	1.46E-05	1.50E-05
Marine eutrophication	Ammonia	Water	kg N eq	2.36E-08	2.44E-08
Marine eutrophication	Ammonium, ion	Air	kg N eq	4.96E-15	5.13E-15
Marine eutrophication	Ammonium, ion	Water	kg N eq	1.61E-05	1.61E-05

Impact category	Substance	Comp.	Unit	Premium 33 clust. S.Giorgio	Decisa 33 clust. S.Giorgio
Marine eutrophication	Nitrate	Air	kg N eq	2.76E-09	2.76E-09
Marine eutrophication	Nitrate	Water	kg N eq	8.28E-04	8.47E-04
Marine eutrophication	Nitric oxide	Air	kg N eq	1.43E-14	1.48E-14
Marine eutrophication	Nitrite	Water	kg N eq	1.92E-07	1.92E-07
Marine eutrophication	Nitrogen dioxide	Air	kg N eq	1.24E-06	1.29E-06
Marine eutrophication	Nitrogen oxides	Air	kg N eq	5.53E-04	5.54E-04
Marine eutrophication	Nitrogen, total	Water	kg N eq	1.21E-10	1.25E-10
Marine eutrophication	**Total**		**kg N eq**	**1.41E-03**	**1.43E-03**
Freshwater ecotoxicity	Alachlor	Soil	CTUe	8.09E-03	8.36E-03
Freshwater ecotoxicity	Atrazine	Soil	CTUe	5.19E-03	5.36E-03
Freshwater ecotoxicity	Chlorothalonil	Soil	CTUe	4.76E-03	4.78E-03
Freshwater ecotoxicity	Chlorpyrifos	Soil	CTUe	3.29E-03	3.40E-03
Freshwater ecotoxicity	Isoproturon	Soil	CTUe	3.12E-02	3.22E-02
Freshwater ecotoxicity	Metolachlor	Soil	CTUe	7.49E-03	7.72E-03
Freshwater ecotoxicity	Pendimethalin	Soil	CTUe	7.87E-03	8.14E-03
Freshwater ecotoxicity	Terbuthylazin	Soil	CTUe	1.02E-02	1.05E-02
Freshwater ecotoxicity	**Total**		**CTUe**	**7.80E-02**	**8.05E-02**
Human tox. canc. eff.	**Total**		**CTUh**	**0.00E+00**	**0.00E+00**
Human tox. non-canc. eff.	**Total**		**CTUh**	**0.00E+00**	**0.00E+00**

The results obtained for the four product systems are very similar, with slightly greater impacts with regard to the product “La Decisa 33 cl cluster packaging” which, however, it is recalled, was assessed on the basis of forecast data.

4.4.5 Beverage industry products: normalization and weighting

To conclude the presentation of the results obtained by applying the proposed methodology to the four beverage industry products, the last step provides for the final calculation of the single score nitrogen impact indicator, after execution of normalization and calculation and application of the weighting factors.

The nitrogen impact assessment profile results after normalization are shown, for the four analyzed product systems, in the Table 4.34.

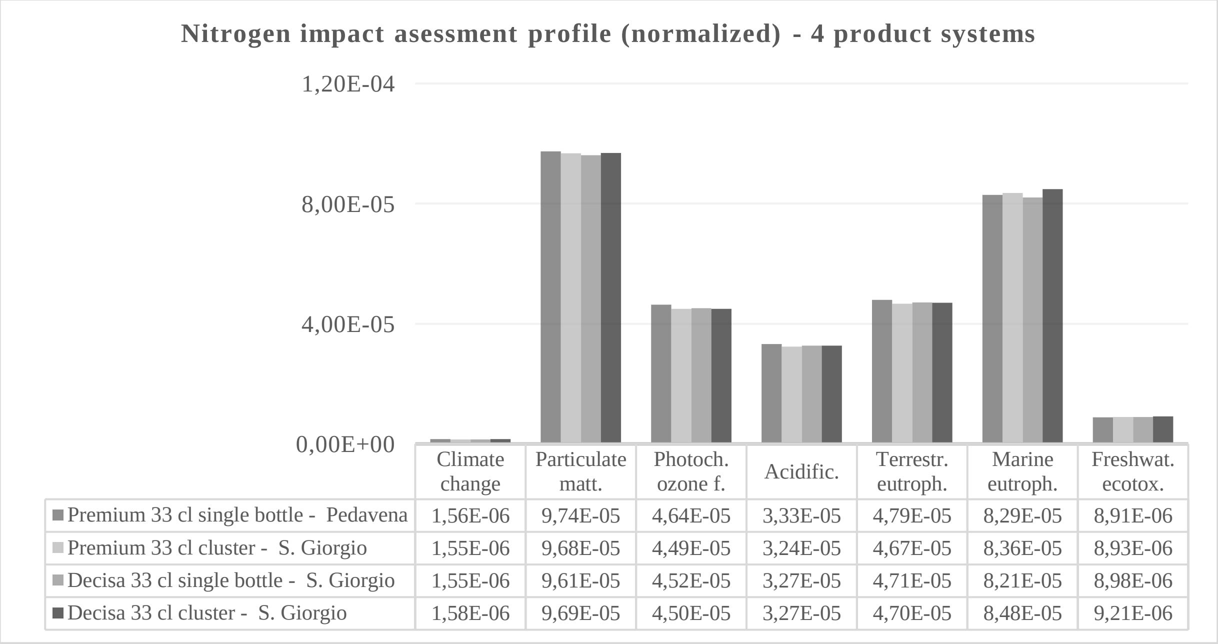
Table 4.34. *Results of normalized impact assessment profile calculated for the four analyzed product systems of the beverage industry. Normalization factors extracted from Benini et al. (2014).*

Impact category	Normaliz. factor	Premium 33 s.b. Pedavena	Premium 33 clust. S.Giorgio	Decisa 33 s.b. S.Giorgio	Decisa 33 clust. S.Giorgio
Climate change	9.22E+03	1.56E-06	1.55E-06	1.55E-06	1.58E-06

Impact category	**Normaliz. factor**	**Premium 33 s.b. Pedavena**	**Premium 33 clust. S.Giorgio**	**Decisa 33 s.b. S.Giorgio**	**Decisa 33 clust. S.Giorgio**
Particulate matter	3.80E+00	9.74E-05	9.68E-05	9.61E-05	9.69E-05
Photochemical ozone formation	3.17E+01	4.64E-05	4.49E-05	4.52E-05	4.50E-05
Acidification	4.73E+01	3.33E-05	3.24E-05	3.27E-05	3.27E-05
Terrestrial eutrophication	1.76E+02	4.79E-05	4.67E-05	4.71E-05	4.70E-05
Marine eutrophication	1.69E+01	8.29E-05	8.36E-05	8.21E-05	8.48E-05
Freshwater ecotoxicity	8.74E+03	8.91E-06	8.93E-06	8.98E-06	9.21E-06
Human toxicity, cancer effects	3.69E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human toxicity, non-cancer effects	5.33E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Once again, the results are null for the categories human toxicity cancer effect and human toxicity non-cancer effect because of the cut-off criterion applied.

While not being the direct comparison between the four product systems one of the objectives of this application, as above stated, the results of the normalized profiles are shown in a single graph in the Figure 4.10, not representing the results equal to 0 of the categories human toxicity cancer effect and human toxicity non cancer effect.



	Climate change	Particulate matt.	Photoch. ozone f.	Acidific.	Terrestr. eutroph.	Marine eutroph.	Freshwat. ecotox.
■ Premium 33 cl single bottle - Pedavena	1,56E-06	9,74E-05	4,64E-05	3,33E-05	4,79E-05	8,29E-05	8,91E-06
■ Premium 33 cl cluster - S. Giorgio	1,55E-06	9,68E-05	4,49E-05	3,24E-05	4,67E-05	8,36E-05	8,93E-06
■ Decisa 33 cl single bottle - S. Giorgio	1,55E-06	9,61E-05	4,52E-05	3,27E-05	4,71E-05	8,21E-05	8,98E-06
■ Decisa 33 cl cluster - S. Giorgio	1,58E-06	9,69E-05	4,50E-05	3,27E-05	4,70E-05	8,48E-05	9,21E-06

Figure 4.10. *Graphic representation of the normalized impact assessment profile results for the four analyzed product systems of the beverage industry.*

Unlike the normalized profiles obtained in previous applications, in this case the greatest impact resulted for the particulate matter impact category, followed in the ranking by the category marine eutrophication. This result is due both to the lower nitrate emission contribution, as previously highlighted, and to the normalization factors chosen for the calculation. The normalization factor for the category particulate matter is in fact quite small, this tending to amplify the result compared to the other categories to which are attributed bigger factors. The degree of subjectivity introduced by normalization, in this case, focuses on the impact category associated with particulate emissions, thus changing the expected order that, considering the inventory results, should have produced, as the most impacting category, marine eutrophication because associated with nitrate emissions.

The results relating to the calculation of the weighting factors are reported below, starting from the results of category reactive nitrogen calculation for the selected impact categories (Table 4.35): these are propaedeutic to the calculation of the weighting factors and are reported separately to ensure the readability of the Tables.

Table 4.35. *Results of category reactive nitrogen calculation for the four analyzed product systems of the beverage industry. Results propaedeutic to the weighting factors calculation.*

Impact category	**Substance**	**Comp.**	**Premium 33 s.b. Pedavena**	**Premium 33 clust. S.Giorgio**	**Decisa 33 s.b. S.Giorgio**	**Decisa 33 clust. S.Giorgio**
Climate change	Dinitrogen monox.	Air	3.46E-05	3.43E-05	3.44E-05	3.51E-05
Climate change	Nitrogen fluoride	Air	2.80E-18	2.69E-18	2.80E-18	2.73E-18
Climate change	**Total**		**3.46E-05**	**3.43E-05**	**3.44E-05**	**3.51E-05**
Particulate matter	Ammonia	Air	1.32E-04	1.30E-04	1.33E-04	1.34E-04
Particulate matter	Nitric oxide	Air	1.14E-14	1.12E-14	1.16E-14	1.16E-14
Particulate matter	Nitrogen dioxide	Air	9.93E-07	9.73E-07	1.01E-06	1.01E-06
Particulate matter	Nitrogen oxides	Air	4.47E-04	4.33E-04	4.35E-04	4.33E-04
Particulate matter	Partic. < 10μm	Air	2.09E-08	2.04E-08	2.11E-08	2.11E-08
Particulate matter	Partic. < 2.5μm	Air	1.52E-05	1.47E-05	1.47E-05	1.47E-05
Particulate matter	**Total**		**5.95E-04**	**5.79E-04**	**5.84E-04**	**5.83E-04**
Photoch. ozone form.	Nitric oxide	Air	1.14E-14	1.12E-14	1.16E-14	1.16E-14
Photoch. ozone form.	Nitrogen dioxide	Air	9.93E-07	9.73E-07	1.01E-06	1.01E-06
Photoch. ozone form..	Nitrogen oxides	Air	4.47E-04	4.33E-04	4.35E-04	4.33E-04
Photoch. ozone form.	**Total**		**4.48E-04**	**4.34E-04**	**4.36E-04**	**4.34E-04**
Acidification	Ammonia	Air	1.32E-04	1.30E-04	1.33E-04	1.34E-04
Acidification	Nitric oxide	Air	1.14E-14	1.12E-14	1.16E-14	1.16E-14
Acidification	Nitrogen dioxide	Air	9.93E-07	9.73E-07	1.01E-06	1.01E-06
Acidification	Nitrogen oxides	Air	4.47E-04	4.33E-04	4.35E-04	4.33E-04
Acidification	**Total**		**5.80E-04**	**5.64E-04**	**5.69E-04**	**5.69E-04**
Terrestrial eutrophication	Ammonia	Air	1.32E-04	1.30E-04	1.33E-04	1.34E-04
Terrestrial eutrophication	Ammonium, ion	Air	4.52E-14	4.43E-14	4.58E-14	4.58E-14
Terrestrial eutrophication	Nitrate	Air	2.24E-08	2.23E-08	2.63E-08	2.23E-08
Terrestrial eutrophication	Nitric oxide	Air	1.14E-14	1.12E-14	1.16E-14	1.16E-14
Terrestrial eutrophication	Nitrogen dioxide	Air	9.93E-07	9.73E-07	1.01E-06	1.01E-06
Terrestrial eutrophication	Nitrogen oxides	Air	4.47E-04	4.33E-04	4.35E-04	4.33E-04
Terrestrial eutrophication	**Total**		**5.80E-04**	**5.64E-04**	**5.69E-04**	**5.69E-04**

Impact category	Substance	Comp.	Premium 33 s.b. Pedavena	Premium 33 clust. S.Giorgio	Decisa 33 s.b. S.Giorgio	Decisa 33 clust. S.Giorgio
Marine eutrophication	Ammonia	Air	1.32E-04	1.30E-04	1.33E-04	1.34E-04
Marine eutrophication	Ammonia	Water	2.41E-08	2.36E-08	2.44E-08	2.44E-08
Marine eutrophication	Ammonium, ion	Air	4.52E-14	4.43E-14	4.58E-14	4.58E-14
Marine eutrophication	Ammonium, ion	Water	1.38E-05	1.60E-05	1.30E-05	1.60E-05
Marine eutrophication	Nitrate	Air	2.24E-08	2.23E-08	2.63E-08	2.23E-08
Marine eutrophication	Nitrate	Water	8.00E-04	8.28E-04	8.01E-04	8.46E-04
Marine eutrophication	Nitric oxide	Air	1.14E-14	1.12E-14	1.16E-14	1.16E-14
Marine eutrophication	Nitrite	Water	1.78E-07	1.92E-07	1.61E-07	1.92E-07
Marine eutrophication	Nitrogen dioxide	Air	9.93E-07	9.73E-07	1.01E-06	1.01E-06
Marine eutrophication	Nitrogen oxides	Air	4.47E-04	4.33E-04	4.35E-04	4.33E-04
Marine eutrophication	Nitrogen, total	Water	1.24E-10	1.21E-10	1.25E-10	1.25E-10
Marine eutrophication	**Total**		**1.39E-03**	**1.41E-03**	**1.38E-03**	**1.43E-03**
Freshwater ecotoxicity	Alachlor	Soil	4.62E-08	4.52E-08	4.68E-08	4.68E-08
Freshwater ecotoxicity	Atrazine	Soil	1.48E-07	1.48E-07	1.50E-07	1.53E-07
Freshwater ecotoxicity	Chlorothalonil	Soil	5.72E-09	8.68E-09	5.73E-09	8.71E-09
Freshwater ecotoxicity	Chlorpyrifos	Soil	1.26E-09	1.24E-09	1.28E-09	1.28E-09
Freshwater ecotoxicity	Isoproturon	Soil	4.61E-07	4.47E-07	4.63E-07	4.63E-07
Freshwater ecotoxicity	Metolachlor	Soil	6.06E-08	6.20E-08	6.14E-08	6.39E-08
Freshwater ecotoxicity	Pendimethalin	Soil	4.13E-07	4.01E-07	4.15E-07	4.15E-07
Freshwater ecotoxicity	Terbuthylazin	Soil	5.90E-08	5.78E-08	5.98E-08	5.98E-08
Freshwater ecotoxicity	**Total**		**1.19E-06**	**1.17E-06**	**1.20E-06**	**1.21E-06**
Human tox. canc. eff.	**Total**		**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
Human tox. non-canc. eff.	**Total**		**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**

Once obtained the category reactive nitrogen results, the weighting factor for the selected impact categories were determined using the internal calculation method specifically designed within the proposed methodology. The output of the calculation are shown in the Table 4.36 where are presented the results of the category reactive nitrogen summation for the four product systems and the calculated weighting factors for each impact category. In this case, as the analysis was extended to four products, the weighting factor calculation was made by summing the category reactive nitrogen results for all the four analyzed product systems, as required by the proposed methodology calculation method.

Table 4.36. *Results of category reactive nitrogen summation for the four product systems and weighting factors calculation determined by applying the internal method proposed within the methodology.*

Impact category	product systems category reactive N	Weighting factors
Climate change	1.38E-04	0.96%
Particulate matter	2.34E-03	16.24%
Photochemical ozone formation	1.75E-03	12.15%
Acidification	2.28E-03	15.83%

Impact category	**product systems category reactive N**	**Weighting factors**
Terrestrial eutrophication	2.28E-03	15.83%
Marine eutrophication	5.62E-03	38.96%
Freshwater ecotoxicity	4.78E-06	0.03%
Human toxicity, cancer effects	0.00E+00	0.00%
Human toxicity, non-cancer effects	0.00E+00	0.00%
Total	**1.44E-02**	**100.00%**

Finally, the weighted nitrogen impact assessment profile and the single score nitrogen impact indictor were calculated for the four analyzed product systems obtaining the results reported in the Table 4.37.

Table 4.37. *Weighting factors (second column), weighted nitrogen assessment profile and single score nitrogen impact indicator (last row) results calculated for the four analyzed product systems of the beverage industry. Weighting factors calculated by the proposed internal method.*

Impact category	**Weighting factors**	**Premium 33 s.b. Pedavena**	**Premium 33 clust. S.Giorgio**	**Decisa 33 s.b. S.Giorgio**	**Decisa 33 clust. S.Giorgio**
Climate change	0.96%	1.50E-08	1.48E-08	1.49E-08	1.52E-08
Particulate matter	16.24%	1.58E-05	1.57E-05	1.56E-05	1.57E-05
Photochemical ozone formation	12.15%	5.63E-06	5.46E-06	5.49E-06	5.47E-06
Acidification	15.83%	5.27E-06	5.13E-06	5.18E-06	5.18E-06
Terrestrial eutrophication	15.83%	7.59E-06	7.38E-06	7.45E-06	7.45E-06
Marine eutrophication	38.96%	3.23E-05	3.26E-05	3.20E-05	3.30E-05
Freshwater ecotoxicity	0.03%	2.95E-09	2.96E-09	2.97E-09	3.05E-09
Human toxicity, cancer effects	0.00%	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human toxicity, non-cancer effects	0.00%	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total (single score nitrogen impact indicator)		**6.66E-05**	**6.63E-05**	**6.57E-05**	**6.69E-05**

It can be noticed that the single score indicator results changed the hypothetical product ranking compared to the reactive nitrogen indicator results. In particular a higher impact value was found for the “Premium 33 cl single bottle – Pedavena plant” product compared to the “Premium 33 cl cluster packaging – S. Giorgio di Nogaro plant”, remaining unchanged the ranking of the other two products. The calculation of the weighted nitrogen impact assessment profile and of the single score nitrogen indicator results was also made using two additional different weighting sets. In particular, in the Table 4.38 are reported the results of the calculation carried out using the weighting set obtained by applying the proposed internal weighting method to the reference product system presented as one of the previous applications.

Table 4.38. *Weighting factors (second column), weighted nitrogen assessment profile and single score nitrogen impact indicator (last row) results calculated for the four analyzed product systems of the beverage industry. Weighting factors calculated by applying the proposed internal method to the reference product system.*

Impact category	Weighting factors	Premium 33 s.b. Pedavena	Premium 33 clust. S.Giorgio	Decisa 33 s.b. S.Giorgio	Decisa 33 clust. S.Giorgio
Climate change	2.675%	4.18E-08	4.14E-08	4.16E-08	4.24E-08
Particulate matter	14.544%	1.42E-05	1.41E-05	1.40E-05	1.41E-05
Photochemical ozone formation	4.578%	2.12E-06	2.06E-06	2.07E-06	2.06E-06
Acidification	14.290%	4.75E-06	4.63E-06	4.68E-06	4.68E-06
Terrestrial eutrophication	14.290%	6.85E-06	6.67E-06	6.73E-06	6.72E-06
Marine eutrophication	49.608%	4.11E-05	4.15E-05	4.07E-05	4.21E-05
Freshwater ecotoxicity	0.010%	8.91E-10	8.93E-10	8.98E-10	9.21E-10
Human toxicity, cancer effects	0.005%	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human toxicity, non-cancer effects	0.005%	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total (single score nitrogen impact indicator)		**6.91E-05**	**6.90E-05**	**6.82E-05**	**6.97E-05**

In the Table 4.39 are instead reported the results obtained using the weighting factors calculated on the basis of the panel set proposed by Huppes and van Oers (2011) as shown in the previous chapter concerning the presentation of the methodology.

Table 4.39. *Weighting factors (second column), weighted nitrogen assessment profile and single score nitrogen impact indicator (last row) results calculated for the four analyzed product systems of the beverage industry. Weighting factors calculated on the basis of the panel set proposed by Huppes and van Oers (2011).*

Impact category	Weighting factors	Premium 33 s.b. Pedavena	Premium 33 clust. S.Giorgio	Decisa 33 s.b. S.Giorgio	Decisa 33 clust. S.Giorgio
Climate change	35.6%	5.55E-07	5.50E-07	5.52E-07	5.63E-07
Particulate matter	10.8%	1.05E-05	1.05E-05	1.04E-05	1.05E-05
Photochemical ozone formation	7.7%	3.59E-06	3.47E-06	3.49E-06	3.48E-06
Acidification	6.2%	2.06E-06	2.01E-06	2.02E-06	2.02E-06
Terrestrial eutrophication	3.6%	1.73E-06	1.68E-06	1.70E-06	1.70E-06
Marine eutrophication	3.6%	2.99E-06	3.02E-06	2.96E-06	3.06E-06
Freshwater ecotoxicity	17.0%	1.51E-06	1.52E-06	1.53E-06	1.57E-06
Human toxicity, cancer effects	9.3%	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human toxicity, non-cancer effects	6.2%	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total (single score nitrogen impact indicator)		**2.298E-05**	**2.272E-05**	**2.266E-05**	**2.288E-05**

The single score impact indicator results obtained by applying the three different weighting sets are also graphically represented in the Figure 4.11 in order to provide a further example of results output format obtained.

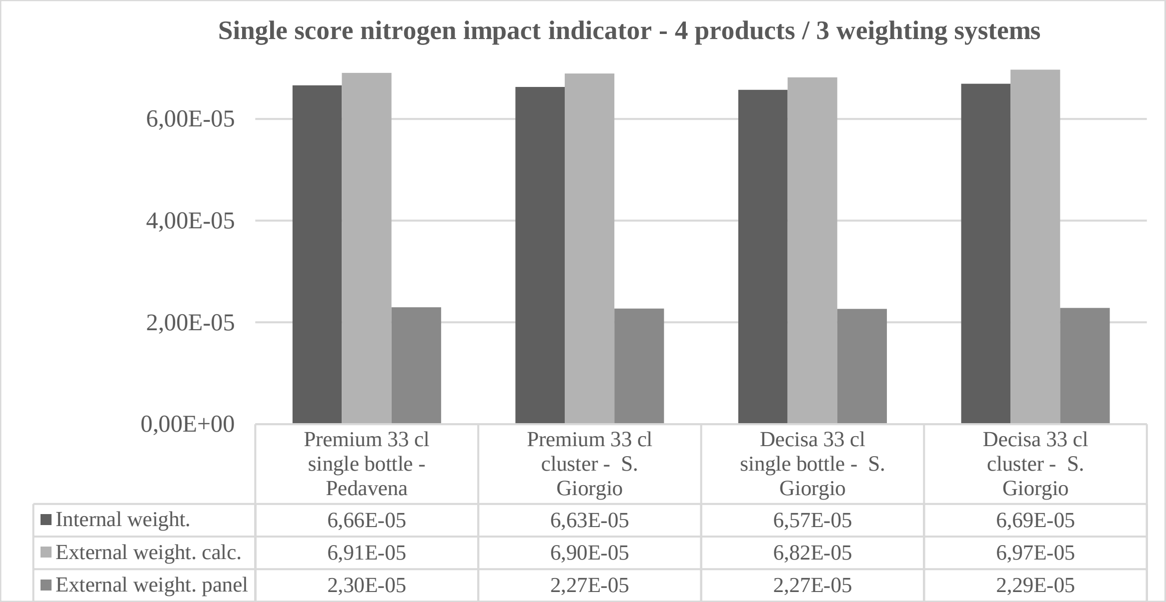


Figure 4.11. *Graphic representation of single score nitrogen impact indicator results for the four analyzed product systems of the beverage industry obtained using 3 different weighting sets.*

It should be noted that the application of the first two weighting sets, calculated starting from the same methodological basis, produces consistent results with regard to the hypothetical ranking of the analyzed product systems. The application of the last set, which instead attributes a rather low weight to the impact category marine eutrophication, produces, as a result, a lesser impact on the product "La Decisa 33 cl cluster packaging – S. Giorgio di Nogaro plant" which was the most impacting in all the previous assessments.

4.4.6 Beverage industry products: interpretation of the results

In addition to what has been highlighted in the preceding paragraphs within the description of the methodology outputs, below are presented further results judged useful both, in general, to show the analytical potential of the methodology and, in particular, to support the phase of interpretation of the results for the specific application carried out.

The in-depth analyzes described relate in particular to two of the four products analyzed, namely "Premium 33 cl single bottle – Pedavena plant" and "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant". The two selected products are in fact, on the one hand, directly comparable as far as the type of packaging is concerned and very similar at production process and recipe level. On the other hand, being manufactured in two different plants, they allow making specific evaluations at the production and plant level. Regarding La Decisa type of beer, furthermore, it must be pointed out that it is currently a new product, which is still being launched on the market and on which the company intends to invest in the near future: a detailed environmental impact analysis was therefore made for this product, becoming strategic also in consideration of the business objectives.

Starting from these considerations, a process contribution analysis, also called "group analysis" in the LCA applications, was made for the two products; specifically, in the Table 4.40, are presented the results for the product "Premium 33 cl single bottle – Pedavena plant" referred to the reactive nitrogen calculation.

This type of analysis was carried out to highlight the contribution to the final results of the various processes that constitute the product life cycle. In the case of the proposed analysis, the process units were grouped into the following:

- vegetal raw materials, comprising all the processes related to vegetal raw materials, namely: barley malt, malt dye, wheat malt, hop;
- packaging, comprising all the process to produce and transport the packaging materials;
- productive process, comprising all the processes carried out in the production plants described in terms of energy consumption, use of chemicals, waste production, wastewater treatment, etc.;
- downstream processes, comprising the product distribution, the use and end-of-life phases.

Table 4.40. *Processes group analysis results for the product "Premium 33 cl single bottle – Pedavena plant" showing the substances contribution to the processes groups in terms of reactive nitrogen [kg/functional unit].*

Substance	Comp.	Vegetal raw mat.	Packaging	Product. process	Downstr. processes	Total processes
2-Aminopropanol	Air	3.44E-13	4.28E-14	6.12E-15	1.09E-14	4.04E-13
2-Aminopropanol	Water	8.26E-13	1.04E-13	1.47E-14	2.62E-14	9.70E-13
2-Nitrobenzoic acid	Air	3.66E-13	3.09E-14	2.02E-15	6.18E-15	4.05E-13
Acephate	Air	8.60E-15	1.17E-13	1.13E-14	3.66E-14	1.73E-13
Acephate	Soil	2.62E-14	1.42E-12	4.53E-14	6.90E-14	1.56E-12
Acetamide	Air	6.56E-15	8.92E-14	8.63E-15	2.80E-14	1.32E-13
Acetamide	Soil	1.23E-14	6.24E-13	2.10E-14	3.07E-14	6.88E-13
Acetochlor	Soil	1.13E-14	8.90E-14	1.68E-14	9.27E-15	1.26E-13
Acetonitrile	Air	1.68E-11	3.68E-10	1.01E-11	3.02E-11	4.25E-10
Acetonitrile	Water	1.68E-10	2.69E-13	8.67E-15	3.30E-14	1.68E-10
Acifluorfen	Air	5.98E-16	8.12E-15	7.86E-16	2.55E-15	1.21E-14
Acifluorfen	Soil	2.56E-17	3.48E-16	3.37E-17	1.09E-16	5.17E-16
Aclonifen	Soil	1.73E-15	8.49E-11	2.50E-18	5.08E-13	8.54E-11
Acrylonitrile	Water	5.17E-14	0.00E+00	0.00E+00	0.00E+00	5.17E-14
Alachlor	Air	5.67E-15	7.70E-14	7.46E-15	2.42E-14	1.14E-13
Alachlor	Soil	4.62E-08	5.19E-14	1.04E-14	1.24E-14	4.62E-08
Aldicarb	Soil	1.68E-13	9.17E-12	2.90E-13	4.37E-13	1.01E-11
Amidosulfuron	Soil	1.50E-16	1.82E-15	4.00E-17	3.26E-16	2.34E-15

Substance	Comp.	Vegetal raw mat.	Packaging	Product. process	Downstr. processes	Total processes
Ammonia	Air	1.08E-04	1.79E-05	5.63E-06	1.03E-06	1.32E-04
Ammonia	Water	2.41E-08	0.00E+00	0.00E+00	0.00E+00	2.41E-08
Ammonia	Soil	5.43E-08	0.00E+00	0.00E+00	0.00E+00	5.43E-08
Ammonia, as N	Water	1.26E-15	0.00E+00	0.00E+00	0.00E+00	1.26E-15
Ammonium carbonate	Air	8.22E-13	8.23E-12	4.54E-11	2.61E-12	5.71E-11
Ammonium, ion	Air	4.52E-14	0.00E+00	0.00E+00	0.00E+00	4.52E-14
Ammonium, ion	Water	3.90E-07	7.91E-06	3.65E-06	1.84E-06	1.38E-05
Aniline	Air	1.71E-12	1.16E-12	1.98E-14	4.36E-14	2.93E-12
Aniline	Water	4.10E-12	2.79E-12	4.75E-14	1.05E-13	7.05E-12
Anthranilic acid	Air	3.48E-13	2.89E-14	1.92E-15	5.86E-15	3.84E-13
Asulam	Soil	9.82E-18	7.80E-17	1.42E-17	7.00E-18	1.09E-16
Atrazine	Air	2.81E-14	3.81E-13	3.69E-14	1.20E-13	5.66E-13
Atrazine	Soil	1.45E-07	2.70E-09	3.90E-11	7.35E-11	1.48E-07
Azoxystrobin	Air	5.32E-15	7.23E-14	6.99E-15	2.27E-14	1.07E-13
Azoxystrobin	Soil	9.81E-11	9.51E-14	5.24E-15	1.03E-14	9.83E-11
Benomyl	Soil	2.99E-14	4.70E-13	1.59E-14	1.48E-14	5.30E-13
Bentazone	Air	5.51E-15	7.48E-14	7.24E-15	2.35E-14	1.11E-13
Bentazone	Soil	3.83E-15	4.78E-11	1.01E-15	2.92E-13	4.81E-11
Benzene, 1-methyl-2-nitro-	Air	3.85E-13	3.26E-14	2.13E-15	6.51E-15	4.26E-13
Bifenox	Soil	9.13E-12	2.82E-19	6.60E-21	5.01E-20	9.13E-12
Bitertanol	Soil	1.17E-11	1.58E-19	4.09E-21	2.78E-20	1.17E-11
Bromoxynil	Soil	2.83E-11	9.49E-16	1.79E-16	9.89E-17	2.83E-11
Bromuconazole	Soil	2.53E-21	3.08E-20	6.63E-22	5.52E-21	3.95E-20
Carbaryl	Air	8.98E-16	1.22E-14	1.18E-15	3.83E-15	1.81E-14
Carbaryl	Soil	4.26E-09	9.29E-15	1.34E-15	1.69E-15	4.26E-09
Carbendazim	Soil	1.32E-12	5.16E-12	6.94E-13	8.05E-13	7.98E-12
Carbetamide	Soil	1.49E-11	3.25E-11	7.85E-12	9.08E-12	6.44E-11
Carbofuran	Soil	5.38E-12	8.45E-11	2.86E-12	2.66E-12	9.54E-11
Carfentrazone-ethyl	Air	1.44E-16	1.96E-15	1.90E-16	6.16E-16	2.91E-15
Carfentrazone-ethyl	Soil	8.87E-13	8.41E-17	8.14E-18	2.64E-17	8.87E-13
Chloramine	Air	1.07E-11	1.94E-12	3.44E-14	8.35E-14	1.27E-11
Chloramine	Water	9.51E-11	1.73E-11	3.07E-13	7.46E-13	1.13E-10
Chloridazon	Soil	3.84E-19	4.68E-18	1.01E-19	8.38E-19	6.00E-18
Chlorimuron-ethyl	Air	3.48E-15	4.73E-14	4.58E-15	1.48E-14	7.02E-14
Chlorimuron-ethyl	Soil	8.98E-14	1.18E-12	6.29E-14	3.36E-13	1.67E-12
Chlormequat	Soil	2.92E-12	1.74E-12	1.78E-13	3.07E-13	5.15E-12
Chlorothalonil	Soil	1.04E-09	4.65E-09	2.79E-12	2.17E-11	5.72E-09
Chlorpyrifos	Air	2.06E-14	2.79E-13	2.70E-14	8.76E-14	4.14E-13
Chlorpyrifos	Soil	1.26E-09	3.04E-12	1.22E-13	4.10E-13	1.26E-09
Chlorsulfuron	Soil	6.13E-21	7.46E-20	1.60E-21	1.34E-20	9.57E-20
Chlortoluron	Soil	5.28E-07	4.07E-14	8.92E-16	7.28E-15	5.28E-07
Choline chloride	Soil	4.33E-19	5.27E-18	1.13E-19	9.44E-19	6.76E-18
Cinidon-ethyl	Soil	3.40E-17	4.14E-16	9.08E-18	7.40E-17	5.31E-16
Clethodim	Air	2.97E-15	4.03E-14	3.90E-15	1.27E-14	5.98E-14
Clethodim	Soil	3.69E-14	4.86E-13	2.59E-14	1.38E-13	6.87E-13
Clodinafop-propargyl	Soil	1.86E-20	2.26E-19	4.86E-21	4.05E-20	2.90E-19
Clomazone	Soil	1.91E-13	6.83E-13	1.01E-13	1.19E-13	1.09E-12
Clopyralid	Soil	1.46E-12	1.99E-14	2.93E-15	3.46E-15	1.48E-12
Cloquintocet-mexyl	Soil	4.67E-21	5.68E-20	1.22E-21	1.02E-20	7.29E-20

Substance	**Comp.**	**Vegetal raw mat.**	**Packaging**	**Product. process**	**Downstr. processes**	**Total processes**
Cloransulam-methyl	Air	2.19E-15	2.97E-14	2.88E-15	9.33E-15	4.41E-14
Cloransulam-methyl	Soil	4.65E-14	6.12E-13	3.26E-14	1.74E-13	8.65E-13
Cyanide	Air	1.30E-09	1.68E-08	2.13E-09	4.76E-09	2.50E-08
Cyanide	Water	2.21E-09	2.44E-08	2.51E-09	6.35E-09	3.55E-08
Cyanoacetic acid	Air	9.66E-11	1.55E-13	5.00E-15	1.90E-14	9.67E-11
Cyfluthrin	Air	8.68E-17	1.18E-15	1.14E-16	3.70E-16	1.75E-15
Cyfluthrin	Soil	6.74E-11	5.05E-15	1.70E-16	2.57E-16	6.74E-11
Cyhalothrin	Soil	1.07E-10	0.00E+00	0.00E+00	0.00E+00	1.07E-10
Cyhalothrin, gamma-	Air	9.62E-16	1.31E-14	1.26E-15	4.10E-15	1.94E-14
Cyhalothrin, gamma-	Soil	4.12E-17	5.60E-16	5.42E-17	1.76E-16	8.31E-16
Cypermethrin	Air	2.20E-16	2.99E-15	2.89E-16	9.37E-16	4.43E-15
Cypermethrin	Soil	9.09E-11	6.84E-12	3.29E-13	3.34E-13	9.84E-11
Cyproconazole	Soil	1.78E-09	2.03E-14	4.46E-16	3.63E-15	1.78E-09
Cyprodinil	Soil	9.64E-09	3.11E-14	6.82E-16	5.56E-15	9.64E-09
Deltamethrin	Soil	3.92E-13	1.39E-14	2.05E-15	2.43E-15	4.10E-13
Diazinon	Soil	1.89E-09	0.00E+00	0.00E+00	0.00E+00	1.89E-09
Dicrotophos	Soil	3.67E-15	2.01E-13	6.35E-15	9.56E-15	2.20E-13
Diethylamine	Air	1.04E-12	6.77E-13	1.55E-14	3.07E-14	1.77E-12
Diethylamine	Water	2.51E-12	1.62E-12	3.72E-14	7.36E-14	4.24E-12
Difenoconazole	Soil	2.93E-14	1.05E-13	1.54E-14	1.83E-14	1.68E-13
Diflubenzuron	Air	1.28E-16	1.74E-15	1.68E-16	5.45E-16	2.58E-15
Diflubenzuron	Soil	1.71E-11	2.24E-10	1.20E-11	6.39E-11	3.17E-10
Diflufenican	Soil	7.65E-11	3.01E-14	6.60E-16	5.38E-15	7.65E-11
Diflufenzopyr-sodium	Soil	1.11E-16	8.73E-16	1.65E-16	9.09E-17	1.24E-15
Dimethachlor	Soil	4.37E-13	1.56E-12	2.30E-13	2.72E-13	2.50E-12
Dimethenamid	Soil	2.21E-15	1.88E-14	3.78E-15	3.65E-15	2.84E-14
Dimethoate	Soil	5.02E-15	6.11E-14	1.34E-15	1.09E-14	7.84E-14
Dimethylamine	Air	2.77E-16	1.49E-14	1.97E-15	1.35E-15	1.85E-14
Dimethylamine	Water	1.12E-09	4.04E-12	1.57E-13	4.97E-13	1.13E-09
Dinitrogen monoxide	Air	2.43E-05	7.84E-06	9.41E-07	1.48E-06	3.46E-05
Dipropylamine	Air	3.37E-13	2.94E-13	4.56E-15	9.55E-15	6.45E-13
Dipropylamine	Water	8.09E-13	7.07E-13	1.10E-14	2.29E-14	1.55E-12
Diquat	Soil	3.63E-15	2.68E-14	1.93E-15	1.69E-15	3.41E-14
Diquat dibromide	Soil	1.06E-21	8.44E-21	1.54E-21	7.58E-22	1.18E-20
Dithianone	Soil	7.47E-16	9.09E-15	1.99E-16	1.62E-15	1.17E-14
Diuron	Soil	1.15E-14	6.28E-13	1.99E-14	2.99E-14	6.89E-13
Epoxiconazole	Soil	2.45E-11	1.60E-14	3.51E-16	2.86E-15	2.45E-11
Esfenvalerate	Air	5.37E-16	7.29E-15	7.06E-16	2.29E-15	1.08E-14
Esfenvalerate	Soil	3.13E-10	3.73E-16	3.16E-17	1.09E-16	3.13E-10
Ethalfluralin	Soil	3.35E-13	1.20E-12	1.77E-13	2.09E-13	1.92E-12
Ethylamine	Air	2.06E-12	4.15E-11	5.93E-14	4.47E-13	4.40E-11
Ethylamine	Water	4.95E-12	9.96E-11	1.42E-13	1.07E-12	1.06E-10
Ethylene diamine	Air	7.99E-13	1.04E-10	5.93E-14	5.82E-13	1.05E-10
Ethylene diamine	Water	1.92E-12	2.50E-10	1.43E-13	1.40E-12	2.54E-10
Fenbuconazole	Soil	3.44E-16	4.18E-15	9.16E-17	7.47E-16	5.36E-15
Fenoxaprop	Air	8.84E-16	1.20E-14	1.16E-15	3.77E-15	1.78E-14
Fenoxaprop	Soil	2.39E-14	3.15E-13	1.67E-14	8.95E-14	4.45E-13
Fenoxaprop-P ethyl ester	Soil	2.50E-12	3.13E-20	8.23E-22	5.52E-21	2.50E-12
Fenpiclonil	Soil	2.74E-13	2.09E-10	1.23E-13	9.78E-13	2.10E-10

Substance	**Comp.**	**Vegetal raw mat.**	**Packaging**	**Product. process**	**Downstr. processes**	**Total processes**
Fenpropidin	Soil	1.45E-10	2.05E-14	4.49E-16	3.66E-15	1.45E-10
Fenpropimorph	Soil	4.99E-10	4.02E-14	9.92E-16	7.12E-15	5.00E-10
Fipronil	Soil	4.77E-14	2.60E-12	8.26E-14	1.24E-13	2.86E-12
Florasulam	Soil	4.61E-12	6.27E-20	1.63E-21	1.11E-20	4.61E-12
Fluazifop-p-butyl	Air	1.10E-15	1.50E-14	1.45E-15	4.71E-15	2.23E-14
Fluazifop-P-butyl	Soil	7.87E-14	3.48E-13	4.27E-14	7.07E-14	5.40E-13
Flucarbazone sodium salt	Soil	2.62E-22	3.19E-21	6.86E-23	5.71E-22	4.09E-21
Fludioxonil	Soil	6.29E-12	1.53E-19	5.06E-21	2.64E-20	6.29E-12
Flufenacet	Air	1.31E-15	1.78E-14	1.72E-15	5.59E-15	2.64E-14
Flufenacet	Soil	1.09E-10	7.65E-16	7.39E-17	2.40E-16	1.09E-10
Flumetsulam	Air	5.71E-16	7.76E-15	7.51E-16	2.43E-15	1.15E-14
Flumetsulam	Soil	2.90E-16	2.42E-15	4.27E-16	3.22E-16	3.46E-15
Flumiclorac-pentyl	Air	1.50E-16	2.04E-15	1.97E-16	6.39E-16	3.02E-15
Flumiclorac-pentyl	Soil	6.43E-18	8.73E-17	8.45E-18	2.74E-17	1.30E-16
Flumioxazin	Air	3.63E-15	4.93E-14	4.77E-15	1.55E-14	7.32E-14
Flumioxazin	Soil	2.62E-14	3.45E-13	1.84E-14	9.81E-14	4.87E-13
Fluroxypyr	Soil	4.37E-12	3.17E-15	6.95E-17	5.67E-16	4.38E-12
Flurtamone	Soil	4.14E-11	1.07E-14	2.35E-16	1.92E-15	4.15E-11
Flusilazole	Soil	1.44E-11	1.17E-14	2.56E-16	2.09E-15	1.44E-11
Fomesafen	Air	1.09E-14	1.48E-13	1.43E-14	4.64E-14	2.20E-13
Fomesafen	Soil	1.39E-13	1.83E-12	9.76E-14	5.21E-13	2.59E-12
Foramsulfuron	Soil	2.46E-17	1.93E-16	3.65E-17	2.01E-17	2.75E-16
Formamide	Air	5.59E-12	1.04E-12	6.32E-15	2.12E-14	6.66E-12
Formamide	Water	1.34E-11	2.49E-12	1.52E-14	5.10E-14	1.60E-11
Glyphosate	Air	2.83E-12	3.84E-11	3.72E-12	1.20E-11	5.70E-11
Glyphosate	Soil	1.98E-08	1.21E-09	6.29E-11	2.64E-09	2.38E-08
Imazamox	Air	9.34E-16	1.27E-14	1.23E-15	3.98E-15	1.88E-14
Imazamox	Soil	3.93E-14	5.17E-13	2.75E-14	1.47E-13	7.31E-13
Imazapyr	Soil	2.84E-18	2.23E-17	4.21E-18	2.32E-18	3.17E-17
Imazaquin	Air	2.92E-15	3.97E-14	3.84E-15	1.25E-14	5.89E-14
Imazaquin	Soil	1.25E-16	1.70E-15	1.65E-16	5.34E-16	2.52E-15
Imazethapyr	Air	6.51E-15	8.84E-14	8.55E-15	2.77E-14	1.31E-13
Imazethapyr	Soil	1.03E-13	1.36E-12	7.25E-14	3.88E-13	1.92E-12
Imidacloprid	Soil	1.20E-10	5.44E-12	1.72E-13	2.59E-13	1.26E-10
Indoxacarb	Soil	2.73E-10	0.00E+00	0.00E+00	0.00E+00	2.73E-10
Ioxynil	Soil	1.27E-11	2.10E-14	4.59E-16	3.75E-15	1.27E-11
Iprodione	Soil	4.54E-13	1.62E-12	2.39E-13	2.83E-13	2.60E-12
Isocyanic acid	Air	1.76E-10	3.21E-08	1.42E-10	1.51E-09	3.40E-08
Isopropylamine	Air	7.48E-13	1.06E-11	1.61E-14	1.15E-13	1.15E-11
Isopropylamine	Water	1.80E-12	2.54E-11	3.86E-14	2.75E-13	2.76E-11
Isoproturon	Soil	4.61E-07	6.92E-13	1.52E-14	1.24E-13	4.61E-07
Isoxaflutole	Soil	8.25E-17	6.49E-16	1.22E-16	6.76E-17	9.22E-16
Kresoxim-methyl	Soil	3.82E-13	6.67E-15	1.46E-16	1.19E-15	3.90E-13
Lactofen	Air	6.61E-16	8.98E-15	8.69E-16	2.82E-15	1.33E-14
Lactofen	Soil	2.83E-17	3.85E-16	3.72E-17	1.21E-16	5.71E-16
Lambda-cyhalothrin	Soil	3.40E-12	7.96E-14	7.60E-15	1.78E-14	3.50E-12
Linuron	Soil	8.24E-12	7.80E-10	1.16E-11	2.65E-11	8.27E-10
Mancozeb	Soil	7.93E-12	5.94E-09	3.56E-12	2.77E-11	5.98E-09
Mefenpyr	Soil	2.04E-11	3.86E-16	8.47E-18	6.91E-17	2.04E-11

Substance	**Comp.**	**Vegetal raw mat.**	**Packaging**	**Product. process**	**Downstr. processes**	**Total processes**
Mefenpyr-diethyl	Soil	9.71E-12	1.21E-19	3.19E-21	2.14E-20	9.71E-12
Mepiquat chloride	Soil	8.54E-11	4.29E-14	1.36E-15	2.04E-15	8.54E-11
Mesotrione	Soil	2.37E-16	1.86E-15	3.51E-16	1.94E-16	2.64E-15
Metamitron	Soil	7.00E-15	5.57E-14	1.03E-14	5.30E-15	7.83E-14
Metazachlor	Soil	5.33E-09	1.02E-11	1.50E-12	1.77E-12	5.34E-09
Methomyl	Soil	1.70E-08	0.00E+00	0.00E+00	0.00E+00	1.70E-08
Methylamine	Air	8.26E-11	3.95E-13	2.26E-14	6.29E-14	8.31E-11
Methylamine	Water	1.98E-10	9.47E-13	5.43E-14	1.51E-13	1.99E-10
Metolachlor	Air	1.76E-14	2.39E-13	2.31E-14	7.49E-14	3.54E-13
Metolachlor	Soil	5.80E-08	2.60E-09	3.19E-12	3.07E-11	6.06E-08
Metribuzin	Air	3.70E-14	5.02E-13	4.86E-14	1.58E-13	7.45E-13
Metribuzin	Soil	1.30E-12	5.36E-10	7.35E-13	4.70E-12	5.43E-10
Monocrotophos	Soil	1.45E-12	1.91E-11	1.02E-12	5.44E-12	2.70E-11
Monoethanolamine	Air	4.00E-09	1.18E-08	8.23E-07	3.09E-10	8.40E-07
Monoethanolamine	Water	9.27E-14	9.28E-13	4.05E-13	3.72E-13	1.80E-12
Napropamide	Soil	4.73E-12	8.59E-12	2.49E-12	2.88E-12	1.87E-11
Nitrate	Air	1.59E-09	1.41E-08	3.73E-10	6.30E-09	2.24E-08
Nitrate	Water	5.67E-04	2.23E-04	5.43E-06	3.95E-06	8.00E-04
Nitrate	Soil	2.90E-09	2.60E-08	2.35E-10	1.17E-08	4.09E-08
Nitric oxide	Air	1.14E-14	0.00E+00	0.00E+00	0.00E+00	1.14E-14
Nitrite	Water	6.31E-10	8.87E-08	6.95E-08	1.97E-08	1.78E-07
Nitrobenzene	Air	2.65E-12	1.20E-12	2.19E-14	4.99E-14	3.92E-12
Nitrobenzene	Water	1.06E-11	4.83E-12	8.76E-14	2.00E-13	1.57E-11
Nitrogen	Water	2.71E-07	7.67E-06	1.05E-06	4.37E-07	9.42E-06
Nitrogen	Soil	9.75E-11	1.35E-09	7.15E-11	4.39E-10	1.96E-09
Nitrogen dioxide	Air	9.93E-07	0.00E+00	0.00E+00	0.00E+00	9.93E-07
Nitrogen fluoride	Air	1.20E-18	1.02E-18	7.19E-20	5.12E-19	2.80E-18
Nitrogen oxides	Air	3.45E-05	2.97E-04	2.26E-05	9.19E-05	4.47E-04
Nitrogen, organic bound	Water	1.57E-08	8.11E-07	2.82E-08	1.60E-07	1.01E-06
Nitrogen, total	Water	1.24E-10	0.00E+00	0.00E+00	0.00E+00	1.24E-10
Orbencarb	Soil	7.91E-13	5.93E-10	3.55E-13	2.77E-12	5.97E-10
Paraquat dichloride	Soil	7.97E-10	0.00E+00	0.00E+00	0.00E+00	7.97E-10
Parathion	Soil	2.40E-14	2.59E-14	2.48E-15	6.16E-15	5.85E-14
Particulates < 10 μm	Air	2.09E-08	0.00E+00	0.00E+00	0.00E+00	2.09E-08
Particulates < 10 μm	Water	5.21E-13	0.00E+00	0.00E+00	0.00E+00	5.21E-13
Particulates < 2.5 μm	Air	9.97E-07	1.07E-05	1.07E-06	2.47E-06	1.52E-05
Particulates > 2.5 μm < 10μm	Air	1.55E-07	1.44E-06	1.22E-07	7.65E-07	2.48E-06
Pendimethalin	Air	1.43E-13	1.94E-12	1.88E-13	6.10E-13	2.89E-12
Pendimethalin	Soil	4.13E-07	3.33E-11	1.76E-12	9.31E-12	4.13E-07
Phenmedipham	Soil	4.32E-16	3.43E-15	6.38E-16	3.27E-16	4.83E-15
Propiconazole	Air	2.05E-15	2.79E-14	2.70E-15	8.75E-15	4.14E-14
Propiconazole	Soil	1.31E-10	1.42E-14	4.00E-16	2.69E-15	1.31E-10
Propylamine	Air	2.34E-13	2.52E-13	1.53E-15	5.15E-15	4.93E-13
Propylamine	Water	5.62E-13	6.04E-13	3.68E-15	1.24E-14	1.18E-12
Pyridate	Soil	1.78E-08	0.00E+00	0.00E+00	0.00E+00	1.78E-08
Simazine	Soil	3.09E-15	2.43E-14	4.59E-15	2.54E-15	3.46E-14
Sulfentrazone	Air	1.57E-14	2.14E-13	2.07E-14	6.71E-14	3.17E-13
Sulfentrazone	Soil	4.96E-13	6.52E-12	3.47E-13	1.86E-12	9.22E-12
t-Butylamine	Air	7.80E-11	9.09E-12	1.65E-14	1.12E-13	8.72E-11

Substance	Comp.	Vegetal raw mat.	Packaging	Product. process	Downstr. processes	Total processes
t-Butylamine	Water	1.87E-10	2.18E-11	3.96E-14	2.69E-13	2.09E-10
Tebupirimphos	Soil	3.26E-16	2.56E-15	4.84E-16	2.67E-16	3.64E-15
Tebutam	Soil	2.10E-11	2.83E-11	1.11E-11	1.27E-11	7.31E-11
Terbuthylazin	Soil	5.90E-08	0.00E+00	0.00E+00	0.00E+00	5.90E-08
Tralkoxydim	Soil	9.39E-11	1.18E-18	3.10E-20	2.08E-19	9.39E-11
Trifloxystrobin	Air	6.81E-17	9.24E-16	8.94E-17	2.90E-16	1.37E-15
Trifloxystrobin	Soil	8.76E-12	3.98E-17	3.84E-18	1.25E-17	8.76E-12
Trifluralin	Air	1.96E-13	2.67E-12	2.58E-13	8.37E-13	3.96E-12
Trifluralin	Soil	1.01E-11	4.88E-11	5.78E-12	1.40E-11	7.87E-11
Trimethylamine	Air	5.04E-13	4.07E-14	2.78E-15	8.46E-15	5.56E-13
Trimethylamine	Water	1.21E-12	9.78E-14	6.66E-15	2.03E-14	1.34E-12
Urea	Water	4.44E-12	3.47E-12	2.63E-14	8.89E-14	8.03E-12
Total	**-**	**7,39E-04**	**5,75E-04**	**4,14E-05**	**1,04E-04**	**1,46E-03**

The same type of analysis presented above was also carried out for the product “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant” obtaining the results reported in the Table 4.41.

Table 4.41. *Processes group analysis results for the product “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant” showing the substances contribution to the processes groups in terms of reactive nitrogen [kg/functional unit].*

Substance	Comp.	Vegetal raw mat.	Packaging	Product. process	Downstr. processes	Total processes
2-Aminopropanol	Air	3.45E-13	4.28E-14	4.12E-15	4.52E-15	3.97E-13
2-Aminopropanol	Water	8.29E-13	1.04E-13	9.90E-15	1.09E-14	9.54E-13
2-Nitrobenzoic acid	Air	3.67E-13	3.10E-14	1.42E-15	3.04E-15	4.03E-13
Acephate	Air	8.38E-15	1.17E-13	7.60E-15	1.53E-14	1.48E-13
Acephate	Soil	2.55E-14	1.42E-12	3.03E-14	5.83E-14	1.53E-12
Acetamide	Air	6.40E-15	8.92E-14	5.81E-15	1.17E-14	1.13E-13
Acetamide	Soil	1.20E-14	6.24E-13	1.49E-14	2.63E-14	6.77E-13
Acetochlor	Soil	1.11E-14	8.91E-14	2.17E-14	1.21E-14	1.34E-13
Acetonitrile	Air	1.66E-11	3.68E-10	1.06E-11	1.71E-11	4.13E-10
Acetonitrile	Water	1.68E-10	2.70E-13	6.06E-15	1.61E-14	1.69E-10
Acifluorfen	Air	5.83E-16	8.13E-15	5.29E-16	1.07E-15	1.03E-14
Acifluorfen	Soil	2.50E-17	3.48E-16	2.27E-17	4.57E-17	4.42E-16
Aclonifen	Soil	1.69E-15	8.49E-11	4.79E-16	5.08E-13	8.55E-11
Acrylonitrile	Water	5.23E-14	0.00E+00	0.00E+00	0.00E+00	5.23E-14
Alachlor	Air	5.53E-15	7.71E-14	5.02E-15	1.01E-14	9.78E-14
Alachlor	Soil	4.68E-08	5.20E-14	7.43E-15	7.63E-15	4.68E-08
Aldicarb	Soil	1.63E-13	9.17E-12	1.94E-13	3.73E-13	9.90E-12
Amidosulfuron	Soil	1.48E-16	1.82E-15	4.43E-17	1.32E-16	2.15E-15
Ammonia	Air	1.09E-04	1.79E-05	5.54E-06	7.30E-07	1.33E-04
Ammonia	Water	2.44E-08	0.00E+00	0.00E+00	0.00E+00	2.44E-08
Ammonia	Soil	5.50E-08	0.00E+00	0.00E+00	0.00E+00	5.50E-08
Ammonia. as N	Water	1.28E-15	0.00E+00	0.00E+00	0.00E+00	1.28E-15
Ammonium carbonate	Air	8.19E-13	8.23E-12	4.49E-11	2.48E-12	5.64E-11
Ammonium. ion	Air	4.58E-14	0.00E+00	0.00E+00	0.00E+00	4.58E-14

Substance	**Comp.**	**Vegetal raw mat.**	**Packaging**	**Product. process**	**Downstr. processes**	**Total processes**
Ammonium. ion	Water	3.89E-07	7.91E-06	2.82E-06	1.83E-06	1.30E-05
Aniline	Air	1.72E-12	1.16E-12	1.62E-14	2.67E-14	2.92E-12
Aniline	Water	4.12E-12	2.80E-12	3.89E-14	6.43E-14	7.02E-12
Anthranilic acid	Air	3.49E-13	2.89E-14	1.34E-15	2.88E-15	3.82E-13
Asulam	Soil	9.63E-18	7.80E-17	1.92E-17	1.06E-17	1.17E-16
Atrazine	Air	2.74E-14	3.81E-13	2.48E-14	5.00E-14	4.84E-13
Atrazine	Soil	1.47E-07	2.70E-09	2.89E-11	5.64E-11	1.50E-07
Azoxystrobin	Air	5.19E-15	7.23E-14	4.71E-15	9.49E-15	9.17E-14
Azoxystrobin	Soil	9.85E-11	9.51E-14	6.88E-15	7.00E-15	9.87E-11
Benomyl	Soil	2.98E-14	4.70E-13	2.19E-14	1.69E-14	5.39E-13
Bentazone	Air	5.37E-15	7.48E-14	4.87E-15	9.81E-15	9.49E-14
Bentazone	Soil	3.78E-15	4.78E-11	1.25E-15	2.88E-13	4.81E-11
Benzene. 1-methyl-2-nitro-	Air	3.87E-13	3.26E-14	1.49E-15	3.20E-15	4.24E-13
Bifenox	Soil	9.16E-12	2.82E-19	7.43E-21	2.06E-20	9.16E-12
Bitertanol	Soil	1.18E-11	1.58E-19	4.71E-21	1.17E-20	1.18E-11
Bromoxynil	Soil	2.84E-11	9.50E-16	2.31E-16	1.29E-16	2.84E-11
Bromuconazole	Soil	2.50E-21	3.09E-20	7.31E-22	2.23E-21	3.63E-20
Carbaryl	Air	8.75E-16	1.22E-14	7.94E-16	1.60E-15	1.55E-14
Carbaryl	Soil	4.32E-09	9.29E-15	8.89E-16	5.83E-16	4.32E-09
Carbendazim	Soil	1.32E-12	5.17E-12	5.03E-13	3.15E-13	7.31E-12
Carbetamide	Soil	1.49E-11	3.25E-11	5.18E-12	2.90E-12	5.56E-11
Carbofuran	Soil	5.37E-12	8.46E-11	3.93E-12	3.03E-12	9.69E-11
Carfentrazone-ethyl	Air	1.41E-16	1.96E-15	1.28E-16	2.58E-16	2.49E-15
Carfentrazone-ethyl	Soil	8.91E-13	8.42E-17	5.48E-18	1.10E-17	8.91E-13
Chloramine	Air	1.07E-11	1.94E-12	2.46E-14	4.97E-14	1.27E-11
Chloramine	Water	9.55E-11	1.74E-11	2.20E-13	4.44E-13	1.13E-10
Chloridazon	Soil	3.80E-19	4.68E-18	1.11E-19	3.39E-19	5.51E-18
Chlorimuron-ethyl	Air	3.40E-15	4.73E-14	3.08E-15	6.21E-15	6.00E-14
Chlorimuron-ethyl	Soil	8.75E-14	1.18E-12	4.31E-14	1.48E-13	1.46E-12
Chlormequat	Soil	2.93E-12	1.74E-12	1.24E-13	1.11E-13	4.91E-12
Chlorothalonil	Soil	1.04E-09	4.66E-09	2.98E-12	3.09E-11	5.73E-09
Chlorpyrifos	Air	2.00E-14	2.79E-13	1.82E-14	3.66E-14	3.54E-13
Chlorpyrifos	Soil	1.28E-09	3.04E-12	8.32E-14	2.19E-13	1.28E-09
Chlorsulfuron	Soil	6.06E-21	7.47E-20	1.77E-21	5.40E-21	8.79E-20
Chlortoluron	Soil	5.30E-07	4.08E-14	9.88E-16	2.95E-15	5.30E-07
Choline chloride	Soil	4.28E-19	5.28E-18	1.25E-19	3.82E-19	6.21E-18
Cinidon-ethyl	Soil	3.36E-17	4.14E-16	1.01E-17	3.00E-17	4.88E-16
Clethodim	Air	2.90E-15	4.04E-14	2.63E-15	5.29E-15	5.12E-14
Clethodim	Soil	3.60E-14	4.86E-13	1.78E-14	6.10E-14	6.01E-13
Clodinafop-propargyl	Soil	1.83E-20	2.26E-19	5.36E-21	1.64E-20	2.66E-19
Clomazone	Soil	1.92E-13	6.83E-13	6.66E-14	4.01E-14	9.82E-13
Clopyralid	Soil	1.46E-12	1.99E-14	1.94E-15	1.17E-15	1.49E-12
Cloquintocet-mexyl	Soil	4.61E-21	5.69E-20	1.35E-21	4.12E-21	6.70E-20
Cloransulam-methyl	Air	2.13E-15	2.97E-14	1.94E-15	3.90E-15	3.77E-14
Cloransulam-methyl	Soil	4.53E-14	6.12E-13	2.23E-14	7.68E-14	7.57E-13
Cyanide	Air	1.29E-09	1.68E-08	1.71E-09	3.27E-09	2.31E-08
Cyanide	Water	2.17E-09	2.44E-08	2.55E-09	4.08E-09	3.32E-08
Cyanoacetic acid	Air	9.69E-11	1.55E-13	3.49E-15	9.29E-15	9.71E-11
Cyfluthrin	Air	8.47E-17	1.18E-15	7.68E-17	1.55E-16	1.50E-15

Substance	**Comp.**	**Vegetal raw mat.**	**Packaging**	**Product. process**	**Downstr. processes**	**Total processes**
Cyfluthrin	Soil	6.83E-11	5.05E-15	1.20E-16	2.15E-16	6.83E-11
Cyhalothrin	Soil	1.09E-10	0.00E+00	0.00E+00	0.00E+00	1.09E-10
Cyhalothrin. gamma-	Air	9.38E-16	1.31E-14	8.51E-16	1.71E-15	1.66E-14
Cyhalothrin. gamma-	Soil	4.02E-17	5.61E-16	3.65E-17	7.35E-17	7.11E-16
Cypermethrin	Air	2.14E-16	2.99E-15	1.94E-16	3.92E-16	3.79E-15
Cypermethrin	Soil	9.21E-11	6.85E-12	3.71E-13	2.73E-13	9.96E-11
Cyproconazole	Soil	1.79E-09	2.03E-14	4.94E-16	1.48E-15	1.79E-09
Cyprodinil	Soil	9.68E-09	3.11E-14	7.55E-16	2.26E-15	9.68E-09
Deltamethrin	Soil	3.93E-13	1.40E-14	1.36E-15	8.19E-16	4.09E-13
Diazinon	Soil	1.92E-09	0.00E+00	0.00E+00	0.00E+00	1.92E-09
Dicrotophos	Soil	3.57E-15	2.01E-13	4.26E-15	8.17E-15	2.17E-13
Diethylamine	Air	1.05E-12	6.77E-13	1.20E-14	1.73E-14	1.76E-12
Diethylamine	Water	2.52E-12	1.63E-12	2.88E-14	4.16E-14	4.21E-12
Difenoconazole	Soil	2.94E-14	1.05E-13	1.02E-14	6.18E-15	1.51E-13
Diflubenzuron	Air	1.25E-16	1.74E-15	1.13E-16	2.28E-16	2.20E-15
Diflubenzuron	Soil	1.66E-11	2.25E-10	8.22E-12	2.82E-11	2.78E-10
Diflufenican	Soil	7.68E-11	3.01E-14	7.32E-16	2.19E-15	7.68E-11
Diflufenzopyr-sodium	Soil	1.09E-16	8.74E-16	2.12E-16	1.18E-16	1.31E-15
Dimethachlor	Soil	4.38E-13	1.56E-12	1.52E-13	9.18E-14	2.25E-12
Dimethenamid	Soil	2.18E-15	1.88E-14	3.33E-15	2.71E-15	2.70E-14
Dimethoate	Soil	4.96E-15	6.11E-14	1.48E-15	4.43E-15	7.20E-14
Dimethylamine	Air	2.67E-16	1.49E-14	1.53E-15	9.32E-16	1.76E-14
Dimethylamine	Water	1.13E-09	4.04E-12	1.12E-13	2.49E-13	1.13E-09
Dinitrogen monoxide	Air	2.44E-05	7.84E-06	9.74E-07	1.13E-06	3.44E-05
Dipropylamine	Air	3.38E-13	2.95E-13	3.81E-15	6.08E-15	6.43E-13
Dipropylamine	Water	8.12E-13	7.07E-13	9.14E-15	1.46E-14	1.54E-12
Diquat	Soil	3.62E-15	2.68E-14	2.65E-15	1.94E-15	3.50E-14
Diquat dibromide	Soil	1.04E-21	8.45E-21	2.08E-21	1.15E-21	1.27E-20
Dithianone	Soil	7.39E-16	9.10E-15	2.21E-16	6.59E-16	1.07E-14
Diuron	Soil	1.12E-14	6.28E-13	1.33E-14	2.56E-14	6.78E-13
Epoxiconazole	Soil	2.46E-11	1.60E-14	3.89E-16	1.16E-15	2.46E-11
Esfenvalerate	Air	5.24E-16	7.30E-15	4.75E-16	9.57E-16	9.26E-15
Esfenvalerate	Soil	3.17E-10	3.74E-16	2.18E-17	4.54E-17	3.17E-10
Ethalfluralin	Soil	3.37E-13	1.20E-12	1.17E-13	7.04E-14	1.72E-12
Ethylamine	Air	2.07E-12	4.15E-11	5.17E-14	6.30E-13	4.43E-11
Ethylamine	Water	4.96E-12	9.96E-11	1.24E-13	1.51E-12	1.06E-10
Ethylene diamine	Air	7.95E-13	1.04E-10	1.96E-13	8.83E-13	1.06E-10
Ethylene diamine	Water	1.91E-12	2.50E-10	4.73E-13	2.12E-12	2.55E-10
Fenbuconazole	Soil	3.40E-16	4.18E-15	1.02E-16	3.03E-16	4.93E-15
Fenoxaprop	Air	8.62E-16	1.20E-14	7.82E-16	1.58E-15	1.52E-14
Fenoxaprop	Soil	2.33E-14	3.15E-13	1.15E-14	3.95E-14	3.89E-13
Fenoxaprop-P ethyl ester	Soil	2.51E-12	3.13E-20	9.50E-22	2.32E-21	2.51E-12
Fenpiclonil	Soil	2.63E-13	2.09E-10	1.31E-13	1.38E-12	2.11E-10
Fenpropidin	Soil	1.46E-10	2.05E-14	4.98E-16	1.49E-15	1.46E-10
Fenpropimorph	Soil	5.02E-10	4.02E-14	1.13E-15	2.96E-15	5.02E-10
Fipronil	Soil	4.64E-14	2.60E-12	5.55E-14	1.06E-13	2.81E-12
Florasulam	Soil	4.63E-12	6.27E-20	1.87E-21	4.65E-21	4.63E-12
Fluazifop-p-butyl	Air	1.08E-15	1.50E-14	9.77E-16	1.97E-15	1.90E-14
Fluazifop-P-butyl	Soil	7.88E-14	3.48E-13	2.84E-14	2.65E-14	4.82E-13

Substance	Comp.	Vegetal raw mat.	Packaging	Product. process	Downstr. processes	Total processes
Flucarbazone sodium salt	Soil	2.59E-22	3.20E-21	7.57E-23	2.31E-22	3.76E-21
Fludioxonil	Soil	6.31E-12	1.53E-19	6.06E-21	1.18E-20	6.31E-12
Flufenacet	Air	1.28E-15	1.78E-14	1.16E-15	2.34E-15	2.26E-14
Flufenacet	Soil	1.10E-10	7.65E-16	4.97E-17	1.00E-16	1.10E-10
Flumetsulam	Air	5.57E-16	7.76E-15	5.05E-16	1.02E-15	9.84E-15
Flumetsulam	Soil	2.85E-16	2.43E-15	5.31E-16	3.28E-16	3.57E-15
Flumiclorac-pentyl	Air	1.46E-16	2.04E-15	1.33E-16	2.67E-16	2.59E-15
Flumiclorac-pentyl	Soil	6.27E-18	8.74E-17	5.68E-18	1.15E-17	1.11E-16
Flumioxazin	Air	3.54E-15	4.93E-14	3.21E-15	6.47E-15	6.26E-14
Flumioxazin	Soil	2.55E-14	3.45E-13	1.26E-14	4.33E-14	4.26E-13
Fluroxypyr	Soil	4.39E-12	3.17E-15	7.70E-17	2.30E-16	4.39E-12
Flurtamone	Soil	4.16E-11	1.07E-14	2.60E-16	7.77E-16	4.16E-11
Flusilazole	Soil	1.44E-11	1.17E-14	2.84E-16	8.48E-16	1.44E-11
Fomesafen	Air	1.06E-14	1.48E-13	9.64E-15	1.94E-14	1.88E-13
Fomesafen	Soil	1.36E-13	1.83E-12	6.69E-14	2.30E-13	2.27E-12
Foramsulfuron	Soil	2.41E-17	1.94E-16	4.71E-17	2.62E-17	2.91E-16
Formamide	Air	5.62E-12	1.04E-12	4.63E-15	1.46E-14	6.67E-12
Formamide	Water	1.35E-11	2.49E-12	1.11E-14	3.50E-14	1.60E-11
Glyphosate	Air	2.76E-12	3.84E-11	2.50E-12	5.04E-12	4.87E-11
Glyphosate	Soil	2.01E-08	1.21E-09	5.29E-11	1.58E-10	2.15E-08
Imazamox	Air	9.11E-16	1.27E-14	8.26E-16	1.67E-15	1.61E-14
Imazamox	Soil	3.83E-14	5.18E-13	1.89E-14	6.49E-14	6.40E-13
Imazapyr	Soil	2.78E-18	2.23E-17	5.43E-18	3.03E-18	3.36E-17
Imazaquin	Air	2.85E-15	3.97E-14	2.58E-15	5.21E-15	5.04E-14
Imazaquin	Soil	1.22E-16	1.70E-15	1.11E-16	2.23E-16	2.16E-15
Imazethapyr	Air	6.34E-15	8.84E-14	5.75E-15	1.16E-14	1.12E-13
Imazethapyr	Soil	1.01E-13	1.36E-12	4.97E-14	1.71E-13	1.68E-12
Imidacloprid	Soil	1.21E-10	5.44E-12	1.15E-13	2.22E-13	1.27E-10
Indoxacarb	Soil	2.77E-10	0.00E+00	0.00E+00	0.00E+00	2.77E-10
Ioxynil	Soil	1.27E-11	2.10E-14	5.08E-16	1.52E-15	1.28E-11
Iprodione	Soil	4.56E-13	1.63E-12	1.58E-13	9.54E-14	2.34E-12
Isocyanic acid	Air	1.70E-10	3.21E-08	1.28E-10	7.52E-10	3.32E-08
Isopropylamine	Air	7.50E-13	1.06E-11	1.40E-14	1.58E-13	1.15E-11
Isopropylamine	Water	1.80E-12	2.55E-11	3.36E-14	3.78E-13	2.77E-11
Isoproturon	Soil	4.63E-07	6.93E-13	1.68E-14	5.02E-14	4.63E-07
Isoxaflutole	Soil	8.09E-17	6.50E-16	1.58E-16	8.81E-17	9.77E-16
Kresoxim-methyl	Soil	3.84E-13	6.68E-15	1.62E-16	4.84E-16	3.91E-13
Lactofen	Air	6.45E-16	8.99E-15	5.85E-16	1.18E-15	1.14E-14
Lactofen	Soil	2.76E-17	3.85E-16	2.51E-17	5.05E-17	4.88E-16
Lambda-cyhalothrin	Soil	3.41E-12	7.96E-14	5.09E-15	7.24E-15	3.50E-12
Linuron	Soil	8.12E-12	7.81E-10	8.29E-12	1.74E-11	8.14E-10
Mancozeb	Soil	7.61E-12	5.94E-09	3.80E-12	3.94E-11	6.00E-09
Mefenpyr	Soil	2.05E-11	3.87E-16	9.39E-18	2.80E-17	2.05E-11
Mefenpyr-diethyl	Soil	9.75E-12	1.21E-19	3.68E-21	9.01E-21	9.75E-12
Mepiquat chloride	Soil	8.57E-11	4.29E-14	9.10E-16	1.75E-15	8.58E-11
Mesotrione	Soil	2.32E-16	1.86E-15	4.53E-16	2.53E-16	2.80E-15
Metamitron	Soil	6.86E-15	5.57E-14	1.37E-14	7.59E-15	8.39E-14
Metazachlor	Soil	5.40E-09	1.02E-11	9.94E-13	5.98E-13	5.41E-09
Methomyl	Soil	1.72E-08	0.00E+00	0.00E+00	0.00E+00	1.72E-08

Substance	**Comp.**	**Vegetal raw mat.**	**Packaging**	**Product. process**	**Downstr. processes**	**Total processes**
Methylamine	Air	8.29E-11	3.95E-13	2.77E-14	3.37E-14	8.34E-11
Methylamine	Water	1.99E-10	9.48E-13	6.65E-14	8.08E-14	2.00E-10
Metolachlor	Air	1.71E-14	2.39E-13	1.56E-14	3.13E-14	3.03E-13
Metolachlor	Soil	5.88E-08	2.60E-09	2.33E-12	2.26E-11	6.14E-08
Metribuzin	Air	3.60E-14	5.03E-13	3.27E-14	6.59E-14	6.37E-13
Metribuzin	Soil	1.26E-12	5.36E-10	6.25E-13	4.49E-12	5.43E-10
Monocrotophos	Soil	1.41E-12	1.91E-11	6.99E-13	2.40E-12	2.36E-11
Monoethanolamine	Air	4.01E-09	1.18E-08	8.03E-09	4.78E-10	2.44E-08
Monoethanolamine	Water	9.24E-14	9.28E-13	2.66E-13	2.22E-13	1.51E-12
Napropamide	Soil	4.75E-12	8.59E-12	1.65E-12	9.15E-13	1.59E-11
Nitrate	Air	1.38E-09	1.42E-08	3.06E-10	1.04E-08	2.63E-08
Nitrate	Water	5.71E-04	2.23E-04	4.03E-06	2.97E-06	8.01E-04
Nitrate	Soil	2.49E-09	2.62E-08	2.63E-10	2.00E-08	4.89E-08
Nitric oxide	Air	1.16E-14	0.00E+00	0.00E+00	0.00E+00	1.16E-14
Nitrite	Water	6.15E-10	8.87E-08	5.19E-08	1.97E-08	1.61E-07
Nitrobenzene	Air	2.66E-12	1.20E-12	1.77E-14	2.99E-14	3.91E-12
Nitrobenzene	Water	1.07E-11	4.83E-12	7.09E-14	1.20E-13	1.57E-11
Nitrogen	Water	2.72E-07	7.67E-06	7.99E-07	2.21E-07	8.96E-06
Nitrogen	Soil	9.12E-11	1.36E-09	5.99E-11	5.59E-10	2.07E-09
Nitrogen dioxide	Air	1.01E-06	0.00E+00	0.00E+00	0.00E+00	1.01E-06
Nitrogen fluoride	Air	1.20E-18	1.02E-18	5.17E-20	5.32E-19	2.80E-18
Nitrogen oxides	Air	3.38E-05	2.98E-04	1.63E-05	8.73E-05	4.35E-04
Nitrogen. organic bound	Water	1.52E-08	8.12E-07	2.18E-08	1.63E-07	1.01E-06
Nitrogen. total	Water	1.25E-10	0.00E+00	0.00E+00	0.00E+00	1.25E-10
Orbencarb	Soil	7.60E-13	5.93E-10	3.79E-13	3.93E-12	5.98E-10
Paraquat dichloride	Soil	8.07E-10	0.00E+00	0.00E+00	0.00E+00	8.07E-10
Parathion	Soil	2.41E-14	2.59E-14	1.72E-15	5.03E-15	5.67E-14
Particulates < 10 μm	Air	2.11E-08	0.00E+00	0.00E+00	0.00E+00	2.11E-08
Particulates < 10 μm	Water	5.28E-13	0.00E+00	0.00E+00	0.00E+00	5.28E-13
Particulates < 2.5 μm	Air	9.76E-07	1.07E-05	7.80E-07	2.22E-06	1.47E-05
Particulates > 2.5 μm < 10μm	Air	1.47E-07	1.44E-06	9.68E-08	7.49E-07	2.44E-06
Pendimethalin	Air	1.40E-13	1.95E-12	1.27E-13	2.55E-13	2.47E-12
Pendimethalin	Soil	4.15E-07	3.33E-11	1.21E-12	4.12E-12	4.15E-07
Phenmedipham	Soil	4.23E-16	3.44E-15	8.45E-16	4.68E-16	5.17E-15
Propiconazole	Air	2.00E-15	2.79E-14	1.82E-15	3.66E-15	3.54E-14
Propiconazole	Soil	1.31E-10	1.42E-14	3.93E-16	1.10E-15	1.31E-10
Propylamine	Air	2.35E-13	2.52E-13	1.12E-15	3.59E-15	4.92E-13
Propylamine	Water	5.65E-13	6.05E-13	2.69E-15	8.62E-15	1.18E-12
Pyridate	Soil	1.81E-08	0.00E+00	0.00E+00	0.00E+00	1.81E-08
Simazine	Soil	3.03E-15	2.44E-14	5.92E-15	3.30E-15	3.66E-14
Sulfentrazone	Air	1.54E-14	2.14E-13	1.39E-14	2.81E-14	2.71E-13
Sulfentrazone	Soil	4.83E-13	6.53E-12	2.38E-13	8.19E-13	8.07E-12
t-Butylamine	Air	7.83E-11	9.09E-12	1.37E-14	1.46E-13	8.76E-11
t-Butylamine	Water	1.88E-10	2.18E-11	3.30E-14	3.49E-13	2.10E-10
Tebupirimphos	Soil	3.20E-16	2.57E-15	6.24E-16	3.48E-16	3.86E-15
Tebutam	Soil	2.11E-11	2.84E-11	7.31E-12	3.99E-12	6.07E-11
Terbuthylazin	Soil	5.98E-08	0.00E+00	0.00E+00	0.00E+00	5.98E-08
Tralkoxydim	Soil	9.43E-11	1.18E-18	3.58E-20	8.77E-20	9.43E-11
Trifloxystrobin	Air	6.64E-17	9.25E-16	6.02E-17	1.21E-16	1.17E-15

Substance	Comp.	Vegetal raw mat.	Packaging	Product. process	Downstr. processes	Total processes
Trifloxystrobin	Soil	8.80E-12	3.99E-17	2.59E-18	5.21E-18	8.80E-12
Trifluralin	Air	1.92E-13	2.67E-12	1.74E-13	3.50E-13	3.38E-12
Trifluralin	Soil	1.01E-11	4.89E-11	3.86E-12	5.65E-12	6.84E-11
Trimethylamine	Air	5.06E-13	4.08E-14	1.94E-15	4.16E-15	5.53E-13
Trimethylamine	Water	1.22E-12	9.78E-14	4.66E-15	9.98E-15	1.33E-12
Urea	Water	4.46E-12	3.47E-12	1.91E-14	5.73E-14	8.01E-12
Total	**-**	**7,42E-04**	**5,75E-04**	**3,15E-05**	**9,74E-05**	**1,45E-03**

From the evaluations carried out for both the product systems, it appeared that about 90% of the impacts, expressed in terms of reactive nitrogen, is attributable to the upstream processes: exactly about 50% to the vegetal raw materials production, transformation and transport and about 40% to the packaging production and transport. These results are better represented graphically in the Figures 4.12 and 4.13 referring to the reactive nitrogen processes contribution respectively for the product “Premium 33 cl single bottle – Pedavena plant” (Figure 4.12) and for the product “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant” (Figure 4.13).

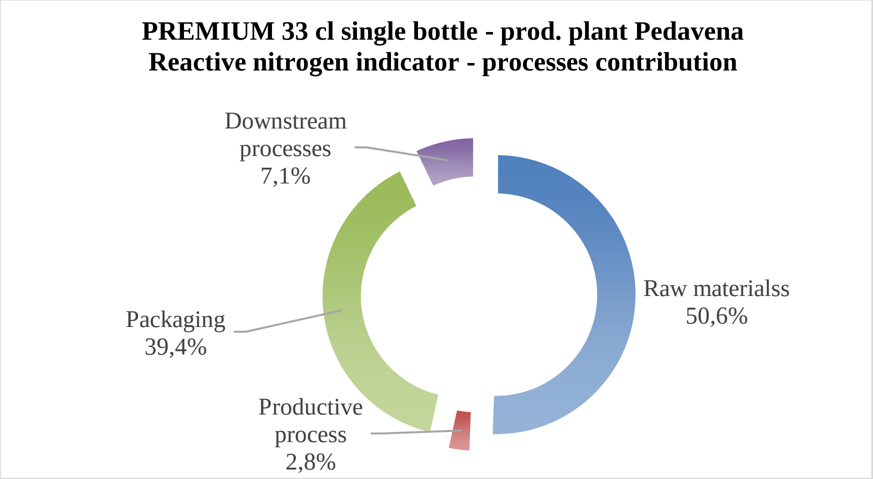


Figure 4.12. *Graphic representation of the reactive nitrogen contribution to the life cycle processes for the product “Premium 33 cl single bottle – Pedavena plant”.*

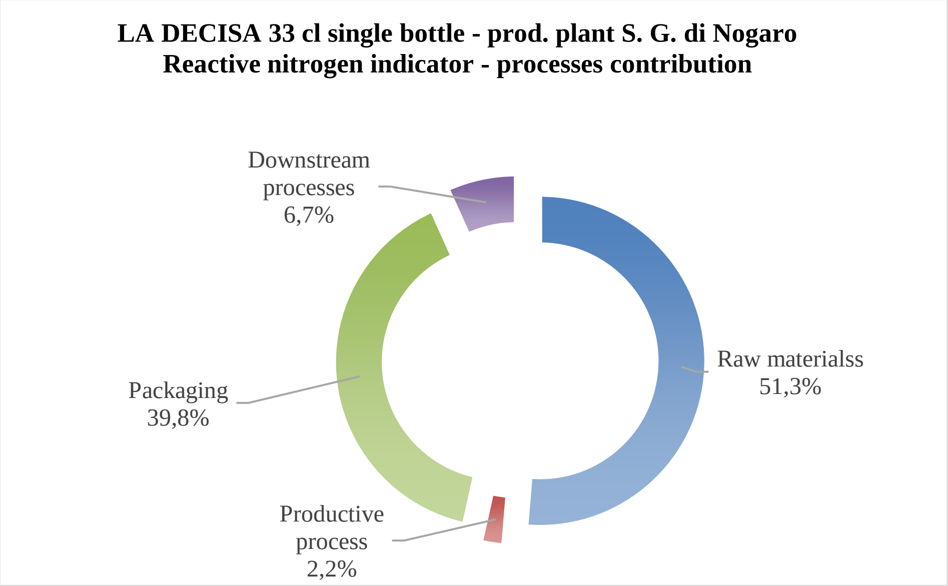


Figure 4.13. *Graphic representation of the reactive nitrogen contribution to the life cycle processes for the product "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant".*

By further deepening the analysis, it emerged that the main contributions to the reactive nitrogen indicator were attributable to the nitrate emission to water for processes of barley cultivation and malt production and to the glass bottle production.

An analogue group analysis was also conducted at characterization level, highlighting the contribution to the process groups of the selected impact categories. The results obtained, with reference to the product "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant", are shown in the Table 4.42.

Table 4.42. *Processes group analysis results at characterization level for the product "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant" showing the substances and impact categories contribution to the processes groups.*

Category	Substance	Comp.	Unit	Veg. raw mater.	Packag.	Produc. process	Downstr. process.
Climate change	Dinitr. monox.	Air	kg CO_2 eq	1.02E-02	3.27E-03	4.05E-04	4.72E-04
Climate change	Nitrogen fluoride	Air	kg CO_2 eq	9.74E-14	8.33E-14	4.21E-15	4.33E-14
Climate change	**Total**		**kg CO_2 eq**	**1.02E-02**	**3.27E-03**	**4.05E-04**	**4.72E-04**
Particulate matter	Ammonia	Air	kg $PM_{2.5}$ eq	8.82E-06	1.45E-06	4.49E-07	5.92E-08
Particulate matter	Nitric oxide	Air	kg $PM_{2.5}$ eq	2.75E-16	0.00E+00	0.00E+00	0.00E+00
Particulate matter	Nitrogen dioxide	Air	kg $PM_{2.5}$ eq	2.39E-08	0.00E+00	0.00E+00	0.00E+00
Particulate matter	Nitrogen oxides	Air	kg $PM_{2.5}$ eq	8.12E-07	7.41E-06	4.02E-07	2.11E-06
Particulate matter	Particul. <10µm	Air	kg $PM_{2.5}$ eq	8.89E-08	0.00E+00	0.00E+00	0.00E+00
Particulate matter	Particul.< 2.5µm	Air	kg $PM_{2.5}$ eq	1.10E-05	2.79E-04	1.40E-05	3.93E-05
Particulate matter	**Total**		**kg $PM_{2.5}$ eq**	**2.07E-05**	**2.88E-04**	**1.48E-05**	**4.15E-05**
Photoch. ozone form.	Nitric oxide	Air	kg NMVOC eq	2.48E-14	0.00E+00	0.00E+00	0.00E+00

Category	**Substance**	**Comp.**	**Unit**	**Veg. raw mater.**	**Packag.**	**Produc. process**	**Downstr. process.**
Photoch. ozone form.	Nitrogen dioxide	Air	kg NMVOC eq	3.30E-06	0.00E+00	0.00E+00	0.00E+00
Photoch. ozone form.	Nitrogen oxides	Air	kg NMVOC eq	1.11E-04	9.78E-04	5.36E-05	2.87E-04
Photoch. ozone for.	**Total**		**kg NMVOC eq**	**1.14E-04**	**9.78E-04**	**5.36E-05**	**2.87E-04**
Acidification	Ammonia	Air	molc H+ eq	4.00E-04	6.56E-05	2.03E-05	2.68E-06
Acidification	Nitric oxide	Air	molc H+ eq	2.80E-14	0.00E+00	0.00E+00	0.00E+00
Acidification	Nitrogen dioxide	Air	molc H+ eq	2.45E-06	0.00E+00	0.00E+00	0.00E+00
Acidification	Nitrogen oxides	Air	molc H+ eq	8.22E-05	7.24E-04	3.97E-05	2.12E-04
Acidification	**Total**		**molc H+ eq**	**4.84E-04**	**7.89E-04**	**6.00E-05**	**2.15E-04**
Terr. eutrophication	Ammonia	Air	molc N eq	1.79E-03	2.93E-04	9.10E-05	1.20E-05
Terr. eutrophication	Ammonium, ion	Air	molc N eq	7.49E-13	0.00E+00	0.00E+00	0.00E+00
Terr. eutrophication	Nitrate	Air	molc N eq	1.93E-08	1.99E-07	4.28E-09	1.45E-07
Terr. eutrophication	Nitric oxide	Air	molc N eq	1.62E-13	0.00E+00	0.00E+00	0.00E+00
Terr. eutrophication	Nitrogen dioxide	Air	molc N eq	1.41E-05	0.00E+00	0.00E+00	0.00E+00
Terr. eutrophication	Nitrogen oxides	Air	molc N eq	4.73E-04	4.17E-03	2.28E-04	1.22E-03
Terr. eutrophication	**Total**		**molc N eq**	**2.27E-03**	**4.46E-03**	**3.19E-04**	**1.23E-03**
Marine eutrophic.	Ammonia	Air	kg N eq	1.22E-05	2.00E-06	6.20E-07	8.17E-08
Marine eutrophic.	Ammonia	Water	kg N eq	2.44E-08	0.00E+00	0.00E+00	0.00E+00
Marine eutrophic.	Ammonium, ion	Air	kg N eq	5.13E-15	0.00E+00	0.00E+00	0.00E+00
Marine eutrophic.	Ammonium, ion	Water	kg N eq	3.90E-07	7.93E-06	2.83E-06	1.83E-06
Marine eutrophic.	Nitrate	Air	kg N eq	1.71E-10	1.76E-09	3.79E-11	1.28E-09
Marine eutrophic.	Nitrate	Water	kg N eq	5.71E-04	2.23E-04	4.04E-06	2.97E-06
Marine eutrophic.	Nitric oxide	Air	kg N eq	1.48E-14	0.00E+00	0.00E+00	0.00E+00
Marine eutrophic.	Nitrite	Water	kg N eq	6.14E-10	8.85E-08	5.19E-08	1.97E-08
Marine eutrophic.	Nitrogen dioxide	Air	kg N eq	1.29E-06	0.00E+00	0.00E+00	0.00E+00
Marine eutrophic.	Nitrogen oxides	Air	kg N eq	4.32E-05	3.80E-04	2.09E-05	1.12E-04
Marine eutrophic.	Nitrogen, total	Water	kg N eq	1.25E-10	0.00E+00	0.00E+00	0.00E+00
Marine eutrophic.	**Total**		**kg N eq**	**6.28E-04**	**6.14E-04**	**2.84E-05**	**1.16E-04**
Freshw. ecotoxicity	Alachlor	Soil	CTUe	8.36E-03	9.29E-09	1.33E-09	1.36E-09
Freshw. ecotoxicity	Atrazine	Soil	CTUe	5.16E-03	9.48E-05	1.01E-06	1.98E-06
Freshw. ecotoxicity	Chlorothalonil	Soil	CTUe	5.73E-04	2.55E-03	1.63E-06	1.69E-05
Freshw. ecotoxicity	Chlorpyrifos	Soil	CTUe	3.39E-03	8.08E-06	2.21E-07	5.82E-07
Freshw. ecotoxicity	Isoproturon	Soil	CTUe	3.22E-02	4.83E-08	1.17E-09	3.50E-09
Freshw. ecotoxicity	Metolachlor	Soil	CTUe	7.10E-03	3.14E-04	2.81E-07	2.73E-06
Freshw. ecotoxicity	Pendimethalin	Soil	CTUe	8.14E-03	6.54E-07	2.37E-08	8.08E-08
Freshw. ecotoxicity	Terbuthylazin	Soil	CTUe	1.05E-02	0.00E+00	0.00E+00	0.00E+00
Freshw. ecotoxicity	**Total**		**CTUe**	**7.54E-02**	**2.97E-03**	**3.18E-06**	**2.23E-05**
Hum. tox. canc.	**Total**		**CTUh**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
Hum. tox. non-canc.	**Total**		**CTUh**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**

The same considerations made for the previous results can be made also in this case, with reference to the significant contribution of the upstream processes to the total impact of the product system.

The results of the characterization step are more easily interpretable after the normalization, performed using the reference factors provided within the proposed methodology. The results obtained, with reference again to the product “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant”, are shown in the Table 4.43.

Table 4.43. *Processes group analysis results after normalization for the product "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant" showing the normalized impact categories contribution to the processes groups.*

Category	**Veg. raw material**	**Packag.**	**Productive process**	**Downstr. processes**	**Total processes**
Climate change	1.10E-06	3.54E-07	4.40E-08	5.12E-08	1.55E-06
Particulate matter	5.45E-06	7.58E-05	3.90E-06	1.09E-05	9.61E-05
Photochemical ozone formation	3.61E-06	3.08E-05	1.69E-06	9.05E-06	4.52E-05
Acidification	1.02E-05	1.67E-05	1.27E-06	4.54E-06	3.27E-05
Terrestrial eutrophication	1.29E-05	2.53E-05	1.81E-06	7.01E-06	4.71E-05
Marine eutrophication	3.72E-05	3.63E-05	1.68E-06	6.89E-06	8.21E-05
Freshwater ecotoxicity	8.63E-06	3.40E-07	3.63E-10	2.55E-09	8.98E-06
Human toxicity, cancer effects	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human toxicity, non-cancer effects	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

The same result above highlighted, as for the significant contribution of the upstream processes, can be found by the analysis of the normalized results. Compared to what was obtained with reference to the calculation of reactive nitrogen, in this case, it can be noticed and increasing of the contribution of processes related to packaging compared to the processes related to vegetable raw materials. This trend can be better highlighted after the application of the weighting factors and the calculation of the single score nitrogen impact indicator for the processes groups. The results of these calculations are reported in the Table 4.44, with reference to the product "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant". Since the analysis was carried out on a single product system, the weighting set calculated for the reference product system was applied, instead of the set calculated with the internal weighting method that was expressly referable to the four product systems, as above described.

Table 4.44. *Processes group analysis results after weighting for the product "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant" showing the weighted impact categories contribution to the processes groups and the single score nitrogen impact indicator results (last row). Reference product system weighting factors applied for the calculation.*

Category	**Veg. raw material**	**Packag.**	**Productive process**	**Downstr. processes**	**Total processes**
Climate change	2,95E-08	9,48E-09	1,18E-09	1,37E-09	4,16E-08
Particulate matter	7,93E-07	1,10E-05	5,67E-07	1,59E-06	1,40E-05
Photochemical ozone formation	1,65E-07	1,41E-06	7,74E-08	4,14E-07	2,07E-06
Acidification	1,46E-06	2,38E-06	1,81E-07	6,50E-07	4,68E-06
Terrestrial eutrophication	1,85E-06	3,62E-06	2,59E-07	1,00E-06	6,73E-06
Marine eutrophication	1,84E-05	1,80E-05	8,33E-07	3,42E-06	4,07E-05
Freshwater ecotoxicity	4,47E-10	1,76E-11	1,88E-14	1,32E-13	4,65E-10
Human toxicity, cancer effects	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Human toxicity, non-cancer effects	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Total (single score nitrogen impact indicator)	**2,27E-05**	**3,65E-05**	**1,92E-06**	**7,08E-06**	**6,82E-05**

Also in this case, the results are better represented graphically as in the Figure 4.14 referring to the single score impact indicator processes contribution for the product “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant”. As anticipated, it became clear the change of ranking, in the contribution to the overall impact, of the processes related to packaging (53.5%) compared to the processes related to vegetal raw materials (33.3%).

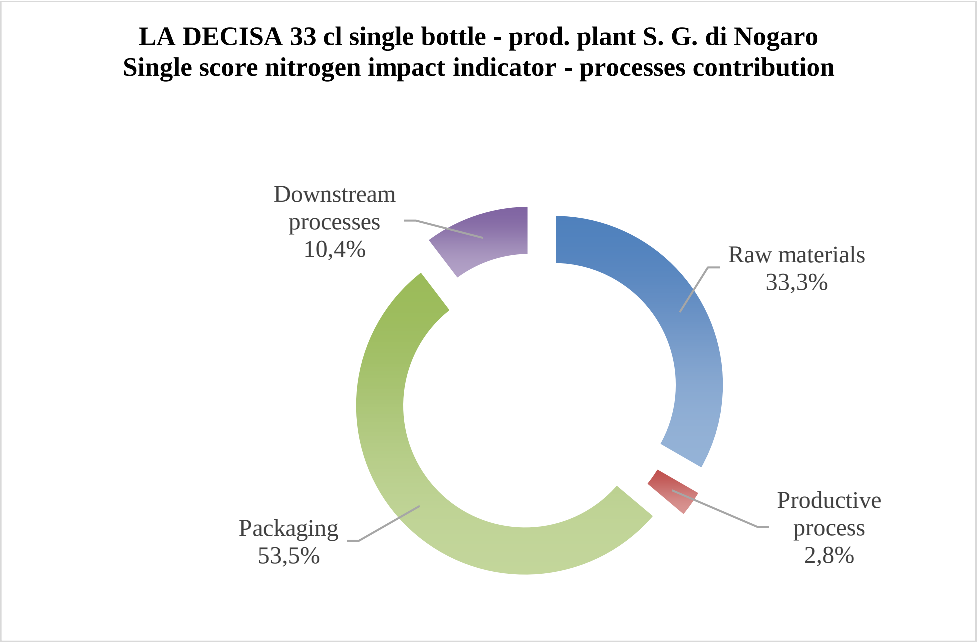


Figure 4.14. *Graphic representation of the single score nitrogen impact indicator contribution to the life cycle processes for the product “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant”.*

For what concern the results expressed as single score impact indicator, the main contribution was attributable to the impact categories particulate matter and marine eutrophication due to the emission of particulate to air, nitrogen oxides to air and nitrate to water, mostly in connection with barley cultivation and malt production processes and with cardboard and glass packaging production.

Examining in detail the production process, which however contributes minimally to the total impact of the life cycle, a specific investigation was made by evaluating the contribution of the following process units:

- electricity consumption, comprising the direct and indirect consumption of electricity of the plants;
- methane consumption, comprising the methane consumption for utilities in the production process service;

- chemicals, related to the use of chemicals in the production process;
- waste, related to the production of waste by the production processes, including packaging used for input products and materials;
- wastewater treatment, relative to the treatment of industrial wastewater before discharge into the sewer system;
- others, comprising, among others, atmospheric emissions, including leakage of refrigerants and ammonia and the purchase of CO_2.

The results of the impact, expressed in terms of single score nitrogen indicator for the impact categories and spread over the process units listed above, are presented in the Tables 4.45 and 4.46 referred, respectively, to the product “Premium 33 cl single bottle – Pedavena plant” (Table 4.45) and to the product “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant” (Table 4.46).

Table 4.45. *Productive process group analysis results expressed as single score nitrogen impact indicator for the product “Premium 33 cl single bottle – Pedavena plant” showing the impact categories contribution. Reference product system weighting set applied for the calculation of indicator values. Null contribution of the categories Human toxicity cancer effect and Human toxicity non-cancer effect not reported.*

Category	Electr. consumpt.	Methane consumpt.	Chemicals	Waste (plant)	Wastewater treatment	Others	Total
Climate change	5.72E-10	3.44E-10	3.04E-11	4.37E-12	4.22E-11	1.44E-10	1.14E-09
Particulate matt.	1.34E-07	9.11E-08	3.16E-08	5.85E-09	1.63E-08	3.78E-07	6.56E-07
Ph. ozone form.	5.21E-08	2.64E-08	4.90E-09	8.82E-10	2.88E-09	2.02E-08	1.07E-07
Acidification	8.30E-08	4.13E-08	1.32E-08	1.38E-09	5.89E-09	8.38E-08	2.29E-07
Terr. eutrophic.	1.28E-07	6.38E-08	1.85E-08	2.13E-09	8.62E-09	1.12E-07	3.32E-07
Mar. eutrophic.	4.35E-07	2.20E-07	4.71E-08	7.17E-09	2.27E-07	2.01E-07	1.14E-06
Freshw. ecotox.	1.43E-14	1.17E-14	3.54E-15	1.17E-16	1.43E-15	1.07E-14	4.17E-14

Table 4.46. *Productive process group analysis results expressed as single score nitrogen impact indicator for the product “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant” showing the impact categories contribution. Reference product system weighting set applied for the calculation of indicator values. Null contribution of the categories Human toxicity cancer effect and Human toxicity non-cancer effect not reported.*

Category	Electr. consumpt.	Methane consumpt.	Chemicals	Waste (plant)	Wastewater treatment	Others	Total
Climate change	3.74E-10	1.48E-10	4.74E-10	3.43E-12	3.14E-11	1.46E-10	1.18E-09
Particulate matt.	9.08E-08	3.91E-08	3.60E-08	3.78E-09	1.22E-08	3.85E-07	5.67E-07
Ph. ozone form.	3.43E-08	1.13E-08	5.94E-09	5.85E-10	2.14E-09	2.32E-08	7.74E-08
Acidification	5.46E-08	1.77E-08	1.52E-08	9.21E-10	4.39E-09	8.84E-08	1.81E-07
Terr. eutrophic.	8.40E-08	2.74E-08	2.15E-08	1.42E-09	6.42E-09	1.19E-07	2.59E-07
Mar. eutrophic.	2.87E-07	9.42E-08	5.61E-08	4.81E-09	1.69E-07	2.22E-07	8.33E-07
Freshw. ecotox.	1.52E-14	5.00E-15	4.32E-15	6.55E-17	1.07E-15	1.07E-14	3.63E-14

It is noted that the most of the total impact is spread over different impact categories (particulate matter, acidification, terrestrial eutrophication, photochemical ozone formation) and not focused only on the category marine eutrophication as instead noted in most of the previous applications.

It was moreover found that the major impacts derive from the consumption of electricity and fuel for the operation of the process equipment and from the process unit named “others”, comprising atmospheric emissions, leakage of refrigerants and ammonia and CO_2 inputs. This result is better highlighted in the Table 4.47 presenting the direct comparison between the two products and the contribution of the process units in which the production process is subdivided.

Table 4.47. *Productive process group analysis results expressed as single score nitrogen impact indicator showing the process units contribution. Comparison between the products “Premium 33 cl single bottle – Pedavena plant” and “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant”. Reference product system weighting set used for the calculation of indicator values.*

Process unit	Premium 33 s.b. Pedavena (single score ind.)	Premium 33 s.b. Pedavena (contrib.)	Decisa 33 s.b. S. Giorgio (single score ind.)	Decisa 33 s.b. S. Giorgio (contrib.)
Electricity Consumption	8.32E-07	33.8%	5.51E-07	28.7%
Methane consumption	4.42E-07	18.0%	1.90E-07	9.9%
Chemicals	1.15E-07	4.7%	1.35E-07	7.0%
Waste (plant)	1.74E-08	0.7%	1.15E-08	0.6%
Wastewater treatment	2.60E-07	10.6%	1.94E-07	10.1%
Others (prod. process)	7.95E-07	32.3%	8.38E-07	43.6%
Total productive process	**2.46E-06**	**100%**	**1.92E-06**	**100%**

Besides highlighting the topics of greater impact in the production process, the results also showed an overall less impact with regard to the production process for obtaining the “La Decisa” beer, as also obtained as a result of the carbon footprint analysis carried out in tandem with the present research work.

This result surely proved a greater efficiency for the San Giorgio di Nogaro plant, which is more modern and technologically advanced than the one in Pedavena. On the other hand, it also emerged that the new product La Decisa, from the point of view of environmental performance, is aligned with the current production mix, thus confirming, also at impact level, the data hypothesized by the company during the design phase for the launch of the product.

As for packaging, as already pointed out, the major impacts were related to glass bottle production: also in this case, for the newly conceived product “La Decisa” that has a new bottle design by Giugiaro, the substantial equivalence at impact level was confirmed, with even a slight improvement, compared to the previous version.

As far as downstream processes are concerned, it was found that the major impacts are related to the distribution and transport of products, while minor impacts are associated with the use phase and end of life.

Once again, it emerged, as a general consideration, that the impact indicator contribute to highlight the significance of different impact categories such as particulate matter, acidification and photochemical ozone formation besides the category marine eutrophication that is predominantly influenced by nitrate emissions. As a consequence, the impact indicator tend to shift the focus towards more typically industrial processes, lessening the contribution of those purely related to cultivation and agri-food production.

As regards the detailed analysis carried out with reference to the product "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant", in the Table 4.48 are reported the results of the process units contribution expressed as single score nitrogen impact indicator sorted in descending order.

Table 4.48. *Life cycle group analysis results expressed as single score nitrogen impact indicator showing the process units contribution for the "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant". Reference product system weighting set used for the calculation of indicator values.*

Process unit	**Decisa 33 s.b. S. Giorgio (single score ind.)**	**Decisa 33 s.b. S. Giorgio (contrib.)**
Glass bottle	3.30E-05	48.45%
Barley malt	1.65E-05	24.21%
Wheat malt	5.91E-06	8.67%
Distribution transport	4.24E-06	6.22%
Glass end-of-life	1.73E-06	2.54%
Cardboard box	1.72E-06	2.52%
Others (productive process)	8.38E-07	1.23%
Pallet	7.73E-07	1.13%
Crown cap	6.83E-07	1.00%
Electricity consumption (prod.)	5.51E-07	0.81%
Consumer transport	5.20E-07	0.76%
Others (distribution)	2.75E-07	0.40%
Home refrigeration	2.58E-07	0.38%
Malt dye	2.56E-07	0.38%
Wastewater treatment (prod.)	1.94E-07	0.28%
Methane consumption (prod.)	1.90E-07	0.28%
Chemicals (prod.)	1.35E-07	0.20%
Labels	1.27E-07	0.19%
Stretch film	5.16E-08	0.08%
Hop	4.72E-08	0.07%
Interlayers	4.31E-08	0.06%
Labels, end-of-life	3.78E-08	0.06%
Top cover	2.97E-08	0.04%
Cap, end-of-life	1.51E-08	0.02%
Waste - productive process	1.15E-08	0.02%

Process unit	**Decisa 33 s.b. S. Giorgio (single score ind.)**	**Decisa 33 s.b. S. Giorgio (contrib.)**
Total	**6.82E-05**	**100%**

The biggest contribution resulted the one related to the glass bottle, followed in the ranking by two of the vegetable raw materials and by the processes of transport for the final product distribution.

Another interesting analysis carried out, is that related to the comparison between single score nitrogen indicator results and carbon footprint indicator results carried out with respect of the whole life cycle. As an example, the results of the carbon footprint indicator of the product "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant" are presented in the Figure 4.15 with reference to the contribution of the different processes in the life cycle. These results are directly comparable with those presented in the previous Figure 4.14 relating to the single score nitrogen footprint indicator of the same product.

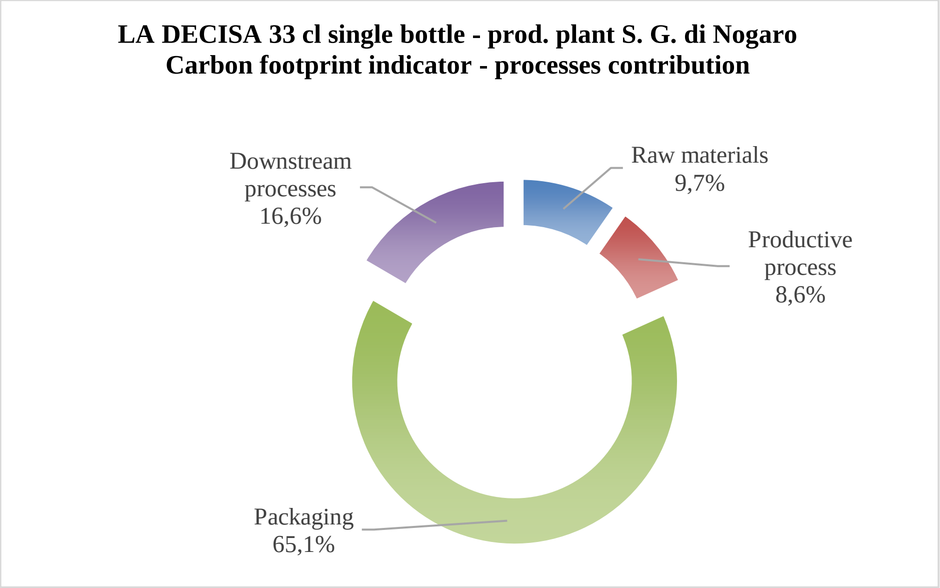


Figure 4.15. *Graphic representation of the carbon footprint indicator contribution for the life cycle processes referred to the product "La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant".*

It emerged that the impact in terms of carbon footprint is predominantly concentrated in the packaging-related processes (65.1 %) and that the contribution of the processes related to vegetable raw materials is, as expected, very low, unlike what was shown by the nitrogen indicator. The results evidenced that, in this case, carbon and nitrogen indicators are not aligned to highlight the contribution of processes in the full life cycle analysis, as already pointed out by research conducted in this field (see in particular Singh and Bakshi, 2015). The two indicators, however, proved to be consistent in relation to the direct comparison of two products with reference to the total life cycle results, both highlighting a greater impact for the product “Premium 33 cl single bottle – Pedavena plant” compared to “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant”, as summarized in the Table 4.49. The results are reported by splitting the stages of the life cycle in vegetal raw materials processes, packaging processes, productive process and downstream processes (comprising use and end-of life phases) contribution.

Table 4.49. *Single score nitrogen impact indicator and carbon footprint indicator [kg CO_2 equiv.] results comparison for the products “Premium 33 cl single bottle – Pedavena plant” and “La Decisa 33 cl single bottle – S. Giorgio di Nogaro plant”.*

Impact category	**Premium 33 s.b. Pedavena Nitrogen single score**	**Decisa 33 s.b. S. Giorgio Nitrogen single score**	**Premium 33 s.b. Pedavena Carbon footprint [kg CO_2 equiv.]**	**Decisa 33 s.b. S. Giorgio Carbon footprint [kg CO_2 equiv.]**
Raw materials	2.27E-05	2.27E-05	4.54E-02	4.50E-02
Packaging	3.65E-05	3.65E-05	3.03E-01	3.03E-01
Productive process	2.46E-06	1.92E-06	6.78E-02	3.99E-02
Downstream processes	7.49E-06	7.08E-06	8.93E-02	7.71E-02
Total	**6.91E-05**	**6.82E-05**	**5.05E-01**	**4.65E-01**

A further indication emerged from the present application is therefore that relating to the complementarity of carbon footprint and nitrogen impact assessment for the evaluation of the life cycle of products. For their specific nature, the two indicators, in fact, can highlight different environmental issues, thus helping the understanding and the deepening of the impacts for different stages of the life cycle.

In conclusion, it can be stated that the set objectives have been achieved, since the methodology was successfully applied to four products of beverage industry, allowing describing and quantifying the environmental impacts of the analyzed product systems with reference to the nitrogen cycle. The analysis also made it possible to identify the processes that most contribute to the overall impact in the life cycle of the products, with a specific focus at productive process level, and to communicate this information to the manufacturing company.

It should also be noted that the information obtained from this application will be used by the company within the environmental management system as part of the certification process according to the international standard ISO 14001:2015 currently in progress. Specifically the results will be used as input into the process of assessing the significance of environmental aspects and for the identification, assessment and management of risk and opportunities.

Chapter 5

Conclusions

This chapter summarizes the conclusions of all the research work presented in the previous chapters. In particular, Section 5.1 refers to the research objectives, describes the methodologies and techniques used and reports the main results obtained during the application phase, also highlighting the limits of the work. In paragraph 5.2 are projected some possible future developments in relation to the research carried out and to the results obtained.

5.1 Conclusions

The proposed research work started from the increasing attention and concern about environmental impacts arising from the nitrogen cycle and the assessments made regarding the overcoming of sustainability limits for this issue. In particular, within the first part of the research, a series of analyzes and evaluations related to the nitrogen cycle and to the associated impacts were performed, considering the relevant reference legislation, the currently proposed nitrogen footprint accounting methods and to the standard requirements for footprint definition and communication. The final objective was to propose and test an innovative methodology for assessing the environmental impacts related to the nitrogen cycle: the activities to achieve the final purpose were developed in the second part of the research, starting from the results of the initial evaluations.

Specifically, addressing the points of weakness found in current nitrogen footprint schemes and applications, the proposed methodology was designed using a comprehensive Life Cycle Assessment (LCA) approach, in order to allow the application to any product system. This approach was developed in order to support the use of database and software for LCA applications and to formulate an assessment method oriented to provide results and information on the actual nature of the impacts generated by a product system in its life cycle. In particular, the methodology was conceived with a multistep framework, consisting of two corollary “conceptual” phases (goal and scope definition and interpretation of the results) and four methodologically operational steps (inventory analysis, assessment at inventory level, impact assessment limited to characterization and impact assessment extended to normalization and weighting). This framework can provide different outputs depending on the goal and scope of the intended application, including a result expressed as a single stand-alone indicator, representing the impact, as alteration of the nitrogen cycle, caused by the analyzed product system. Moreover, the proposed methodology, as well as to carry out an overall assessment of a product system, can be used to provide indications of impacts at process and activity levels, thereby identifying any critical issues in the life cycle and the associated risks and opportunities, in relation to the proposed objectives.

Once completed the design phase, the proposed methodology was tested in several case studies and applications, achieving valid results for all methodological phases and steps. In particular, thanks to a first application to twelve products of the agri-food sector, the methodology was subjected to a partial validation, with satisfactory results, with reference to the step for the calculation of the reactive nitrogen indicator, by making a comparison with published research data.

A second application of the whole methodology was made by analyzing a reference product system specifically created for the purposes of the research consisting of ten product categories each comprising four products. This specific application allowed, in particular, testing the internal weighting method provided by the methodology and, at the same time, obtaining a reference weighting set for the subsequent applications.

Two further applications based on real data were then carried out to complete the phase of testing of the proposed methodology: one relating to the comparison between two methods of cultivation of barley (conventional and organic) and a final assessment carried out on four different products at one of the major Italian companies of the beverage industry. In particular, with regard to the comparison of agricultural processes, the results showed less impact for the organic cultivation method. As regards the application in the beverage industry, the methodology allowed to obtain an assessment of four different products, to highlight the phases of the life cycle causing the greatest impacts, also carrying out a comparison with the results obtained in terms of carbon footprint and, finally, to analyze in detail the performance of a new product being launched in the market.

The performed applications made it possible to test and make improvements to the methodology, by engineering the phase and the steps and by designing and implementing a specific internal weighting method. They also allowed increasing the efficiency in the implementation phase, also thanks to the design of automatic calculation procedures. Finally, the test phases were crucial to select the best

LCA databases to use, and to identify more than 200 nitrogen-containing substances for which to calculate the nitrogen coefficient.

On the other hand, the experimentation phase allowed to achieve the expected results for all the output provided (nitrogen inventory, reactive nitrogen indicator, impact assessment profile and single score impact indicator), according to the defined goal and scope of the specific applications and in line with expectations.

Some limitations related to the methodological approach and to the application performed still emerged during the research and are presented below.

First, it should be noted that, for the specific applications carried out, three specific LCA based databases were used, from which more than 200 nitrogen-containing substances were identified. The databases used are undoubtedly the most complete to support the analyzes made and the cut-off criterion adopted for the selection of the nitrogen-containing substances is sufficiently restrictive to not affect the validity of the results obtained. However, the substance selection process was not completed with respect to all possible outputs of the datasets and could be further deepened. Some hypotheses regarding the interpretation of the outputs provided by the databases have also been made that could affect the nitrogen inventory and reacrive nitrogen indicator results: these assumption are presented in detail in the section concerning the description of the methodology.

In the operational applications, cut-off criteria were adopted, both for inventory and for the impact assessment steps, in the latter case particularly for the impact categories related to toxicity. Regarding the latter issue, to the impact categories related to human toxicity, potentially included in the methodology, null results were associated for all applications, following the adopted cut-off criteria. This result, which should be further elaborated, is still indicative of a low affinity of these categories with topics related to nitrogen cycle alteration. The cut-off criteria applied are however described in detail in the chapter devoted to the applications and are such as not to affect in any way the validity of the results obtained.

Again, with regard to the applications, no specific sensitivity and uncertainty analyzes were carried out, as typically done within in LCA studies, as they did not fall within the scope of the proposed research work.

From a general methodological point of view, it should finally be noted that the proposed methodology, as it relates to a specific environmental issue, provides a partial assessment of the analyzed product system, as it happens indeed for other existing and applied used footprint tools, primarily carbon and water. In this sense, it may be useful, in relation to the intended goal and scope, to make a complementary application of the proposed methodology with other evaluation tools focused on different environmental issues. This aspect was also underlined in the specific application on agricultural processes, with particular reference to the impacts related to the phosphorus cycle and in the application on beverage industry products, with reference to carbon footprint indicator.

Even with the limitations highlighted above, it is believed that an assessment tool of environmental impacts related to the nitrogen cycle, such as the proposed methodology, can be useful for providing consistent assessment results and valid information on a topic that will certainly be central tin the future scientific debate on environmental impacts.

5.2 Future developments

Even though the objectives initially set for research have been satisfying achieved, some interesting perspectives emerged that could be developed with a future work.

Firstly, it is desirable to develop further applications in different fields in order to test the methodology in a large number of cases and to identify areas for improvement and efficiency increasing.

At the same time, in order to increase the accuracy level and efficiency of the calculation, it becomes essential to upgrade the nitrogen coefficient database, further deepening the detail of the database analysis and, at the same time, to extend the automated calculation procedures also including the characterization and final impact assessment phases.

Finally, future ambitious goals might be to try to introduce the presented research topic within the national and international standardization working groups and to establish a partnership to develop the proposed methodology also within the Life Cycle Assessment software applications.

Appendix A

Characterization methods description

In this section are reported the characterization methods used as a reference for the characterization phase and referred to the impact categories selected within the proposed methodology.
The reported methods are those included in ILCD the methodology proposed by JRC and their description is taken from the ILCD Handbook (EC - JRC, 2011) to which reference is made for further details and for bibliographical references.
For each method, a section describing framework and scope and a section presenting the underlying environmental mechanism are included.
The description includes both the midpoint level and the endpoint level of the mechanism to ensure greater comprehension, although only the midpoint level is included in the proposed methodology.

A.1 Climate change

A.1.1 Framework and scope

Climate change involves a number of environmental mechanisms that affect both the Areas of Protection (AoPs) “Human Health” and “Natural Environment”. Climate change models are, in general, developed to assess the future impact on climate resulting from different policy scenarios. The environmental mechanisms used for this impact category have a somewhat different structure, compared to the fate, effect and damage steps applied to many of the other impact categories. Man-made climate change is caused by the emission of greenhouse gases (and by other activities influencing their atmospheric concentration). Greenhouse gases are substances with the ability to absorb infrared radiation from the earth (radiative forcing).
When modelling the radiative forcing of an emission, the change in concentration and radiative forcing is determined, taking into account the residence time of the substance. A globally-recognized model (the Bern model) has been developed by the Intergovernmental Panel on Climate Change (IPCC) that calculates the radiative forcing of all greenhouse gases and branded them Global Warming Potentials (GWP).
The IPCC‘s “GWPs” are recommended for use at midpoint.

- Firstly, at midpoint the GWPs are used directly as characterization factors.
- Secondly, these factors are used to express a combined fate and effect (in terms of radiative forcing), which is then coupled to a modelling of a resulting temperature increase, using the residence time and the radiative forcing of the greenhouse gas.
- Thirdly, the temperature rise results in damage to Human Health and ecosystems, and here several effects are considered, such as an increase in malaria and malnutrition (for Human Health) or disappearance of a species and change in biomass (for ecosystems).

A.1.2 Environmental mechanism

Figure A.1 presents the cause-effect chain for climate change from emission to damage, illustrating the most important pathways (*see bold arrows*).

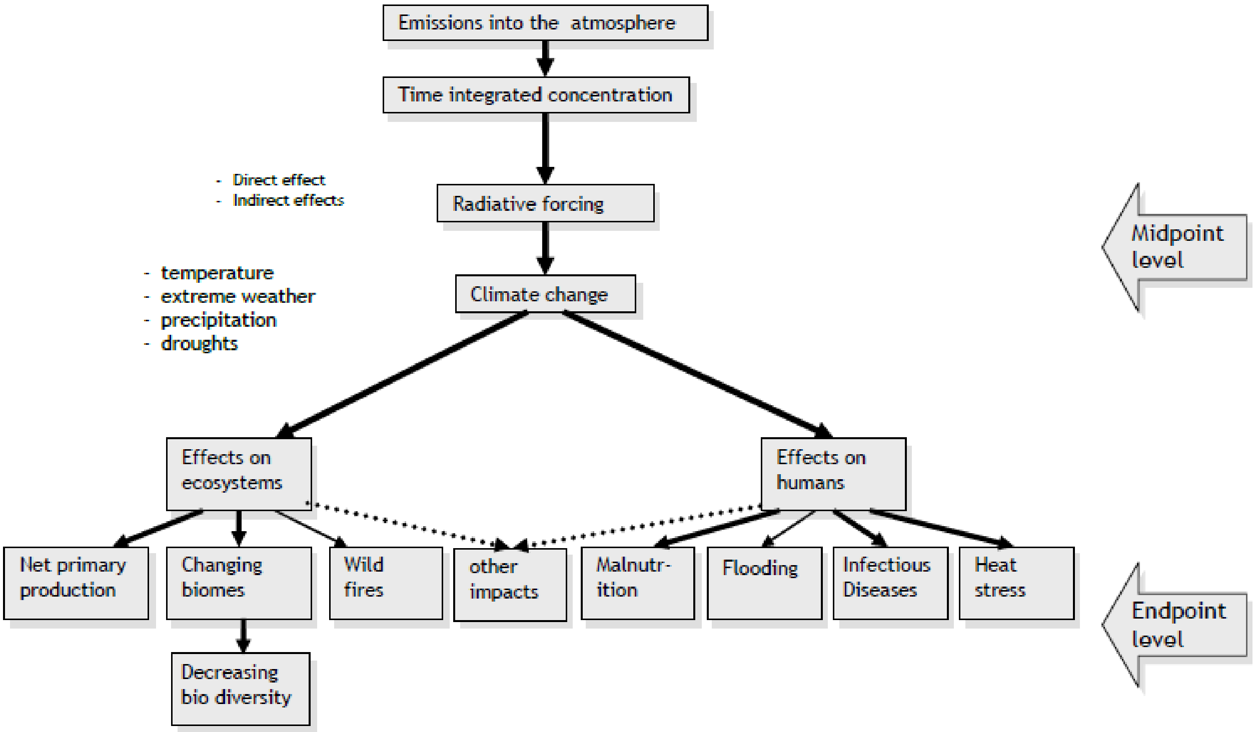


Figure A.1. *Flow diagram for climate change. The thickness of the arrows in the diagram illustrates how important the pathway is in the overall mechanism. Radiative forcing is caused by direct and indirect effects. The box "other impacts" is added, as there are several other impacts, which have not been adequately described to warrant inclusion.*

A.2 Human toxicity

A.2.1 Framework and scope

Models and factors for toxicological effects in Life Cycle Assessment (LCA) must be based on the relative risk and associated consequences of chemicals that are released into the environment. These must build on the principles of comparative risk assessment, while providing indicators linked to the Area of Protection "Human Health".

LCA characterization models and factors for toxic effects must rely on models that account for a chemical's fate in the environment, human exposure, and differences in toxicological response (both likelihood of effects and severity).

The scope and methodology of an LCA differs from that of many approaches adopted for toxicological assessments in a regulatory context. Regulatory assessments of chemical emissions usually have the objective of evaluating whether there will be an unacceptable risk of a toxicological effect to an individual or subpopulation.

The focus in regulatory assessments is generally on ensuring that policy-based limits are not surpassed by exposures at any location or point in time. For example, the maximum likely exposure in the region of an emission may be compared to a tolerable threshold. If this exposure is less than the agreed threshold then no further action is likely to be necessary from a regulatory perspective. It should be noted that these regulatory limits, for example for cancer effects, do not necessarily reflect an absence of an effect and neither are they generally suitable for use in comparative risk assessments where one emission has to be compared against another.

Nevertheless, the underlying mass balance models and basic dose-response information used to determine comparative estimates for LCA are often the same as for regulatory approaches. A key difference is that Life Cycle Impact Assessment (LCIA) takes into account all releases of all substances with a toxicity potential due to the evaluated product over the entire life cycle, regardless of where and when they are released. However, in LCIA all emissions not related to the evaluated product are deliberately excluded from the assessment, e.g. emission of the same chemicals from other products or from sites unrelated to the product. Thus, site specific regulatory assessments, chemical related regulatory assessments and toxicity aspects in LCIA are to be seen complementary in their nature.

Life cycle assessments provide insights for products that are complementary to those of many regulatory risk assessments. In LCA it is desirable to account for the full extent of the likelihood of an effect (recommended midpoint indicator basis) and differences in severity (recommended endpoint indicator basis).

The basis of comparative risk in LCA is the entire global population, using best-estimates complemented with uncertainty insights. The factors must reflect the likelihood of a toxicological impact integrated over time and space that is associated with the release of a quantity of chemical into the environment. This is a fundamental difference from many regulatory approaches, which focus more on realistic peak exposures for individuals compared to acceptable thresholds. Nevertheless, this basis is consistent with the principles already adopted for the assessment of substances such as radionuclides, for other impact categories in LCA such as climate change, as well as in approaches necessary to support cost-benefit analyses.

Contributions of emissions to short-term/acute and local scale effects are presently not addressed in the recommendation. This includes those associated with indoor exposures, direct exposure to products during their use stage, and to exposures in the work place. The focus here is on the contribution of emissions to the risk of toxicological impacts and associated consequences considering the entire human population and dispersed emissions.

A.2.2 Environmental mechanism

Figure A.2 presents the environmental mechanism for human toxicity effects and corresponds to the model framework of fate, exposure and effect assessment.

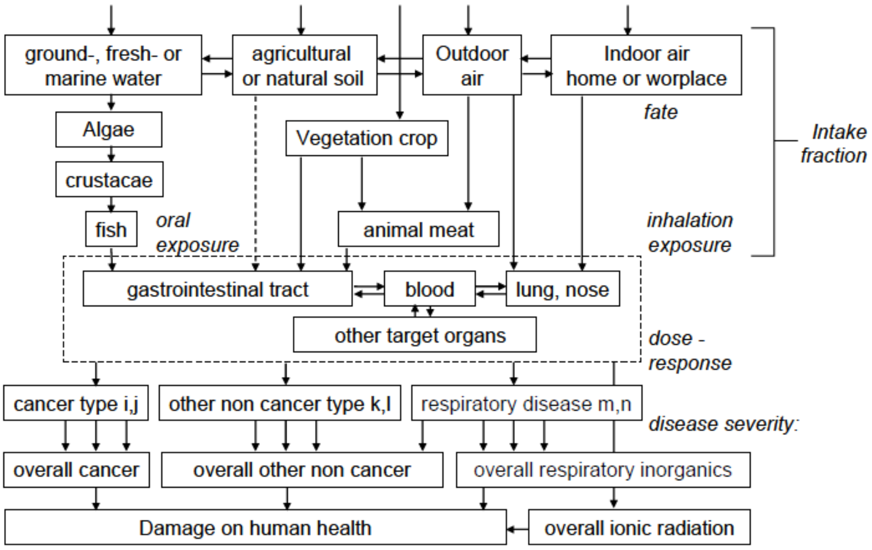


Figure A.2. *Environmental mechanism for the human toxicity effects (including mechanisms for ionizing radiation and respiratory effects associated with particulate matter).*

A.3 Respiratory inorganics/ particulate matter

A.3.1 Framework and scope

Ambient concentrations of particulate matter (PM) are elevated by emissions of primary and secondary particulates. The mechanism for the creation of secondary emissions involves emissions of SO_2 and NO_x that create sulphate and nitrate aerosols. Particulate matter is measured in a variety of ways: total suspended particulates (TSP), particulate matter less than 10 microns in diameter (PM10), particulate matter less than 2.5 microns in diameter (PM2.5) or particulate matter less than 0.1 microns in diameter (PM0.1).

The characterisation factor (*CF*) for particulate matter/respiratory inorganics accounts for the environmental fate (F), exposure (X), dose-response (R) of a pollutant for midpoint factors, and of severity (S) for endpoint factors. See below:

$$CF = S*R*X*F = EF*iF$$

The pollutant can be a single chemical (e.g. CO) or group of agents (e.g. PM2.5). The fate factor relates the emission flow to the mass in the air. The exposure factor determines the change in intake rate per change in mass in the environment. The dose-response slope relates the change in intake with the marginal change in morbidity and mortality cases and the severity is the change in damage per morbidity and mortality case.

The fate and exposure can be combined into an intake fraction (iF). The dose-response and the severity can be combined into the effect factor (EF, in DALY/kginhaled).

The intake fraction describes the fraction of the emission that is taken in by the overall population. Intake fractions can be calculated using fate and exposure models. For the case of particles, it is possible to characterize the fate and exposure further in the cause-effect chain by an intake factor or even an uptake factor because:

1. The exposing particle can be different from the emitted particle (e.g., secondary PM from precursors);
2. The influence of the changing particle size distribution (PSD) throughout time through phenomena like coagulation and nucleation can render the metric of the intake fraction, only a partial representation of exposure.

However, since these two metrics are not yet widespread and not used for other toxic impacts, the metric of the intake fraction is recommended to be used.

Several studies suggest that no thresholds for PM10 should be assumed in the effect calculations- Thus it is recommended to derive dose-response from epidemiological studies assuming linear slopes. However, while the influence of this assumption is unclear based on analogous insights for toxicity effects, it is necessary to stress that the linear dose-response assumption is not well accepted for the high concentrations found in developing countries.

For respiratory inorganics, all available methods are de facto endpoint methods. It is advised to report both the number of cases of different diseases as well as the related Years of Life Lost, Years of Life Disabled and DALYs.

A.3.2 Environmental mechanism

Figure A.3 presents the cause-effect chain of respiratory impacts caused by inorganics and corresponds to the framework of fate, exposure, and effect assessment.

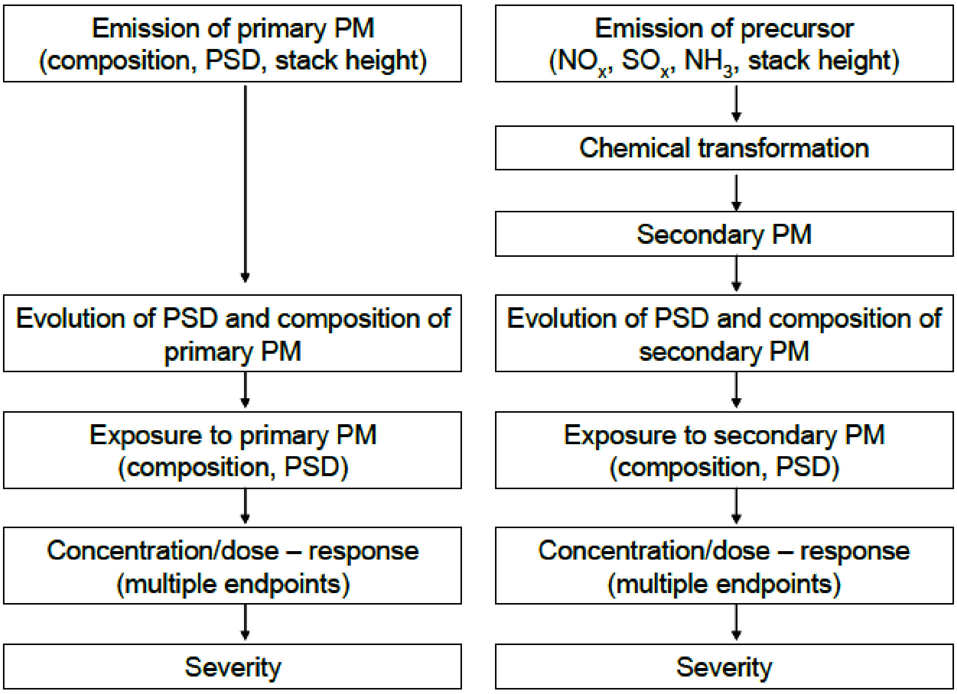


Figure A.3. *Flow diagram for the respiratory inorganics impact category*

A.4 Photochemical ozone formation

A.4.1 Framework and scope

The negative impacts from the photochemically generated pollutants are due to their reactive nature which enables them to oxidise organic molecules on the surfaces they expose. Impacts on humans arise when the ozone and other reactive oxygen compounds are inhaled and come into contact with the surface of the respiratory tract, where they damage tissue and cause respiratory diseases. Impacts on vegetation arise when the reactive compounds attack the surfaces of the plants or enter the stomata of the plant leaves, and cause oxidative damage on photosynthetic organelles. Impacts on man-made materials are caused by oxidation and damage to many types of organic materials which are exposed to ambient air. *NB: the man-made environment is not considered in the recommendations, and therefore the effects on man-made materials will not be considered further*.

The reaction scheme underlying the impact pathway is highly complex and depends on the formula of the concrete VOC, but it can be summarized as:

1. VOCs or CO react with hydroxyl radical OH• in the troposphere and form peroxy radicals, ROO•.
2. The peroxy radicals oxidize NO to NO_2.
3. NO_2 is split by sunlight with formation of NO and release of oxygen atoms.
4. Oxygen atoms react with molecular oxygen, O_2, to form ozone.

Both VOCs and nitrogen oxides are therefore needed for the photochemical ozone formation and should be covered by the characterization models. The heterogeneous spatial distribution of VOC and NOx sources across Europe, and the hundreds of chemical species involved, makes the photochemical formation of ozone on a regional scale highly non-linear and dynamic. It is influenced by meteorological conditions and interaction between the different VOCs – both from anthropogenic and natural sources, such as forests.

The complexity and the number of individual substances for which characterization factors must be calculated leads to a need for simplification which is obtained in two different ways in the available characterization models.

1. The non-linear and dynamic behavior is ignored in a model which represents one or more typical situations in terms of meteorology, atmospheric chemistry and concomitant emissions of other air pollutants.
2. The variation between individual VOCs is (largely) ignored and only a few substance-specific characterization factors are calculated.

The first approach is adopted in the models based on the POCP (Photochemical Ozone Creation Potential) or MIR (Maximum Incremental Reactivity) concept. Here individual characterization factors are provided for many different VOCs. The second approach is adopted in regionally differentiated models which attempt to capture the non-linear nature of the ozone formation with its spatially and temporally determined differences.

Due to the complexity of the underlying chemical reaction schemes and the number of different substances which contribute to photochemical ozone formation, a trade off exists between the degree of detail which can be applied in the fate modelling (including the support of spatially explicit modelling) and the degree of detail applied in the distinction of differences in substance characteristics for the individual VOCs.

The variation in photochemical ozone formation between substances is rather modest, except for halogenated hydrocarbons, CH_4 and CO, which all have relatively low ozone formation potentials. This is revealed by the POCP or MIR values applied for substance differentiation in several methods. The variation caused by spatial differentiation in the modelling of fate and exposure within Europe is considerably higher. Various studies seemed to point at a weakness in the calculations of Photochemical Ozone Creating Potential (POCPs) performed using highly detailed chemical mechanisms. The POCPs were generally obtained using very simplified Lagrangian transport models, using linear trajectories, and the results were thus strongly linked to the chemical regimes that the air parcels were passing in the performed scenario calculations. These new studies indicated that very different results might have been obtained for a different air parcel. It is thus considered preferable to simplify the model on the substance side rather than on the modelling of the dynamic and non-linear nature of the impact pathway.

To ensure consistency with several other impact categories, the ideal midpoint indicator would be the time- and area-integrated concentration increase for ozone in the troposphere. This midpoint would cover impacts later in the environmental mechanism on the areas of protection (AoP) "Human Health" and "Natural Environment" (vegetation).

A.4.2 Environmental mechanism

Figure A.4 shows the cause-effect chain for photochemical ozone formation from airborne emissions of volatile organic compounds, carbon monoxide or nitrogen oxides with the most important pathways highlighted (bold arrows).

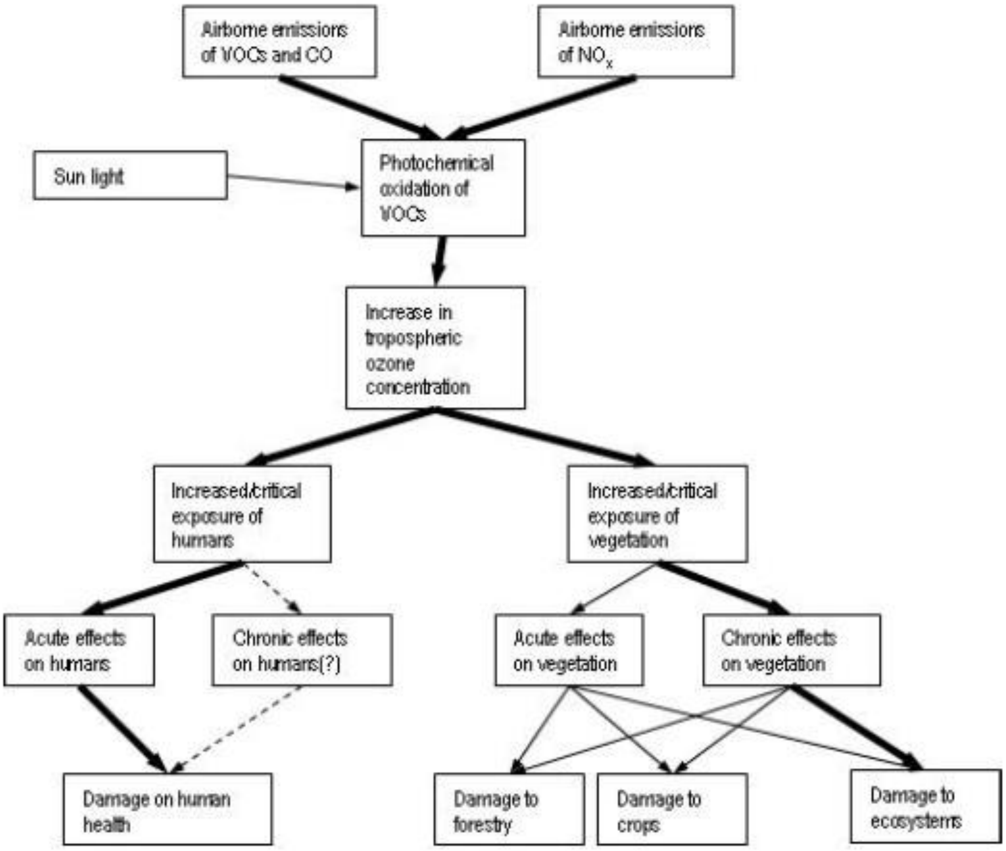


Figure A.4. *Flow diagram for photochemical ozone formation.*

A.5 Acidification

A.5.1 Framework and scope

This impact category addresses the impacts from acidification generated by the emission of airborne acidifying chemicals. Acidification refers literally to processes that increase the acidity of water and soil systems by hydrogen ion concentration. It is caused by atmospheric deposition of acidifying

substances generated largely from emissions of nitrogen oxides (NOx), sulphur dioxide (SO2) and ammonia (NH3), the latter contributing to acidification after it is nitrified (in the soil).
The model framework for the acidification characterization factor is expressed as a fate factor, FF multiplied by an effect factor, EF as per the equation below:

$$CF_{i,ar} = FF * EF = f_{i,ar} \cdot \theta_{i,r\ sensitivity} \cdot * \beta_{dose\text{-}response}$$

where:

- $f_{i,ar}$ represents the fate factor representing the transport of substance (i) in air (a) and the transfer to receptor-environment (r). [dimensionless (kg/kg)].
- $\theta_{i,r\ sensitivity}$ is the fate sensitivity factor of the receptor-environment. It models for example the change in soil parameters such as acidity potential (or base saturation) due to change in acid deposition. It can be calculated as the number of mol H^+ released per kg of deposited pollutant [mol H^+/kg], which depends on the intrinsic property of the chemical and the soil sensitivity.
- $\beta_{dose\text{-}response}$ expresses the effect factor, i.e. the response of the ecosystem to the change in cation capacity (or base saturation) e.g. [Impact/mol H^+] or [-].

A.5.2 Environmental mechanism

The Figure A.5 shows the cause-effect chain for airborne acidifying emissions with the most important pathways highlighted (bold arrows).

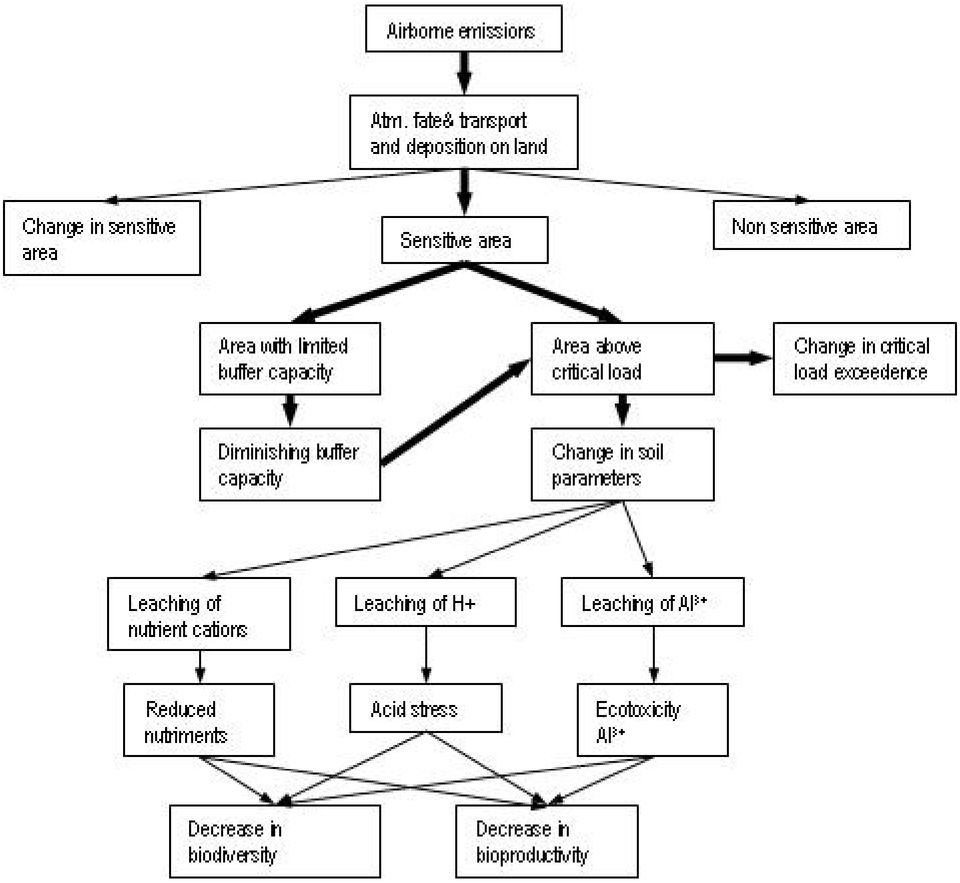


Figure A.5. *Flow diagram for acidification impact category.*

A.6 Eutrophication

A.6.1 Framework and scope

The impact category appears under different names like eutrophication, nutriphication or nutrient enrichment. It addresses the impacts from the macro-nutrients nitrogen and phosphorus in bio-available forms on aquatic and terrestrial ecosystems.

In natural terrestrial systems, the addition of nutrients may change the species composition of the vegetation by favouring those species which benefit from higher levels of nutrients to grow faster than more nutrient efficient plants. This therefore changes the plant community from nutrient-poor (e.g. heath lands, dunes and raised bogs) to nutrient rich and more commonly, due to the widespread dispersion of nutrients, plant communities. The primary impact on the plant community leads to secondary impacts on other species in the terrestrial ecosystem. Terrestrial eutrophication is caused by deposition of airborne emissions of nitrogen compounds like nitrogen oxides (NO_x = NO and NO_2) from combustion processes and ammonia, NH_3 from agriculture. Airborne spreading of phosphorus is not prevalent, and terrestrial eutrophication is therefore mainly associated with nitrogen compounds.

In aquatic systems, the addition of nutrients has a similar primary impact by fertilizing the plants (algae or macrophytes) with a number of consequences for the ecosystem:

Species composition of the plant community changes to more nutrient-demanding species;

Algal blooms create shadowing, filtering the light penetrating into the water mass, changing life conditions from the macrophytes, which need the light for photosynthesis, and for predatory fish which need the light to see and catch their prey;

Oxygen depletion near the bottom of the water body where dead algae deposit and degrade.

All these consequences lead to a change in the species composition and of the function of the exposed aquatic ecosystem.

In aquatic systems it is often one of the macronutrients which limits the growth of algae. Addition of the limiting nutrient will lead to increased primary production, while addition of the nutrient which is not limiting will have no effect on the primary production, and this should be reflected in the life cycle impact assessment. There may be seasonal variations in the pattern of limiting nutrients, but as a general rule, P is the limiting nutrient in freshwater systems while N is limiting nutrient in marine systems.

Freshwater and marine aquatic systems are exposed to water-borne emissions (nitrate, other nitrogen compounds expressed as total N, phosphate and other phosphorus-containing compounds expressed as total P). Marine aquatic systems and very large lakes are also substantially exposed by airborne emissions (NO_x).

One of the consequences of eutrophication is oxygen depletion near the bottom of the exposed systems. Emissions of biological material may also contribute to oxygen depletion when it degrades in the water. This is why some characterisation models provide characterisation factors for waterborne emissions of organic material, expressed as:

- BOD: Biological Oxygen Demand when degraded biologically in water, typically over 5 or 7 days.

or

- COD: Chemical Oxygen Demand when degraded by chemical oxidation.

The inclusion of COD and BOD emissions is not consistent with the impact pathway at midpoint level, but they do contribute to some of the same damages, as emission of nutrients (see Figure A.6). The model framework for the eutrophication characterization factor is expressed as a fate factor: FF multiplied by an effect factor: EF as per equation below:

$$CF_{i,m,r} = FF *\cdot EF = f_{i,mr} \cdot * \beta_{dose\text{-}response}$$

where:

- $f_{i,m,r}$ is the fate factor representing the transport of substance (i) in the media air or water (m) and the transfer to receiving environment (r). [dimensionless (kg/kg)].
- $\beta_{dose\text{-}response}$ is the effect factor expressing the response of the ecosystem to the change in nutrient status e.g. [Impact/kg N or P] or [-].

A.6.2 Environmental mechanism

The Figure A.6 shows the cause-effect chain for airborne acidifying emissions with the most important pathways highlighted (bold arrows).

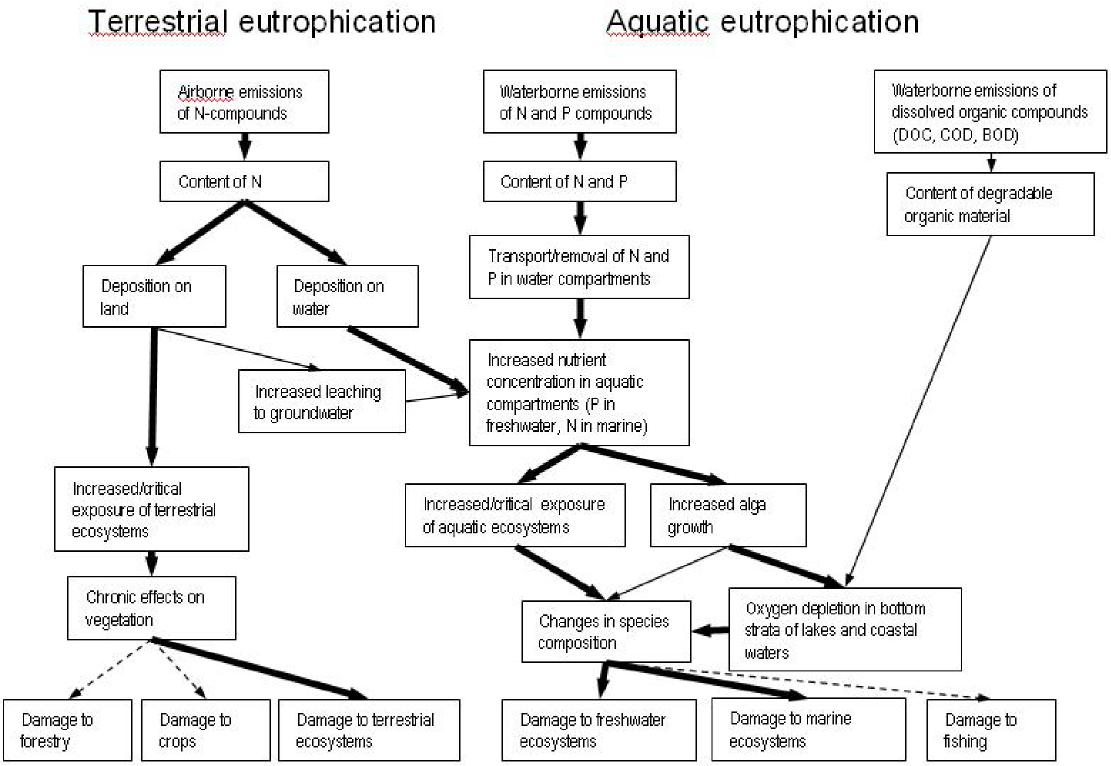


Figure A.6. *Flow diagram for eutrophication.*

A.7 Ecotoxicity

A.7.1 Framework and scope

Models and factors for toxicity effects in LCA must be based on the relative risk and associated consequences of chemicals that are released into the environment. These must build on the principles of comparative risk assessment, while providing indicators linked to the Area of Protection “Natural Environment”.

LCA characterization models and factors for toxicity effects must be based on models that account for a chemical‘s fate in the environment, species exposure, and differences in toxicological response (likelihood of effects and severity).

The scope and methodology of an LCA differs from that of many approaches adopted for toxicological assessments in a regulatory context. In LCA it is desirable to account for the full extent of the likelihood of an effect (recommended midpoint indicator basis) and differences in severity (recommended endpoint indicator basis).

The basis of comparative risk in LCA accounting for the entire global population of species is recommended. This must be based on best-estimates complemented with uncertainty insights. The factors must reflect the likelihood of a toxicological effect integrated over time and space that is associated with the release of a quantity of chemical into the environment. This may be zero.

Contributions of emissions to short-term/acute and local scale effects are not typically addressed in LCAs. The focus here is on the contribution of emissions to the long-term risk of ecotoxicological effects and associated consequences considering all species habitats and disperse emissions.

A.7.2 Environmental mechanism

Figure A.7 shows the cause-effect chain of ecotoxicological impacts and corresponds to the framework of fate and ecotoxicity effect assessment.

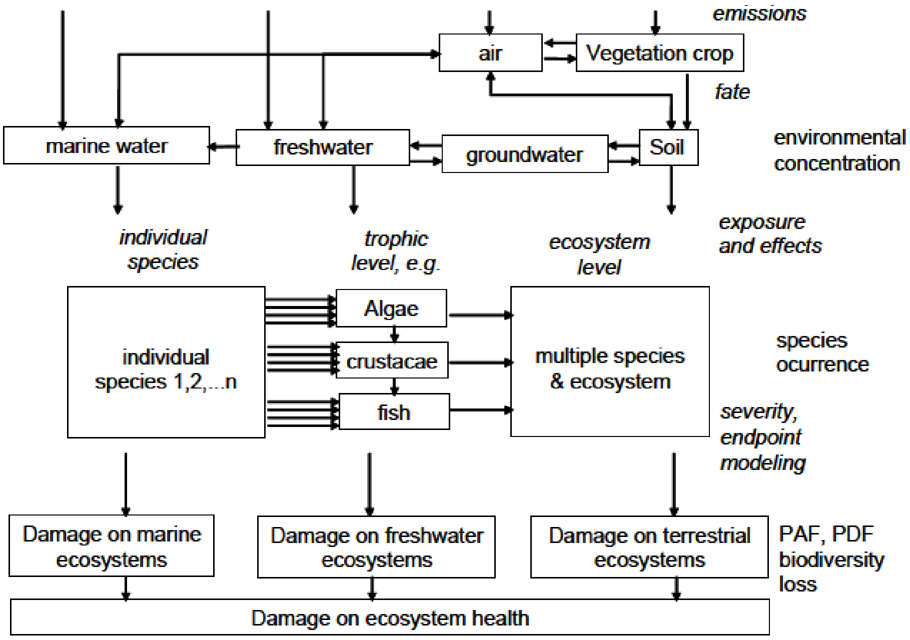


Figure A.7. *Flow diagram for ecotoxicity impacts.*

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